LinCelloy

Processing of High Conductivity Microchannel Linear Cellular Materials

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14. ABSTRACT
Processing of High Conductivity Microchannel Linear Cellular Materials ! Models for paste properties and LCS die designs are nearing completion. ! Quality of honeycomb extrusion has improved dramatically and defects have been minimized. ! Metallurgical properties of alloys from direct oxide reduction can approach those of conventionally processed alloys. ! Due to low pressure drops and thin walls, high efficiency heat exchangers appear feasible for LCAs in a variety of applications. ! High energy adsorption for LCM in high strength alloys has been demonstrated.

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Linear Cellular Alloys for Structural Applications

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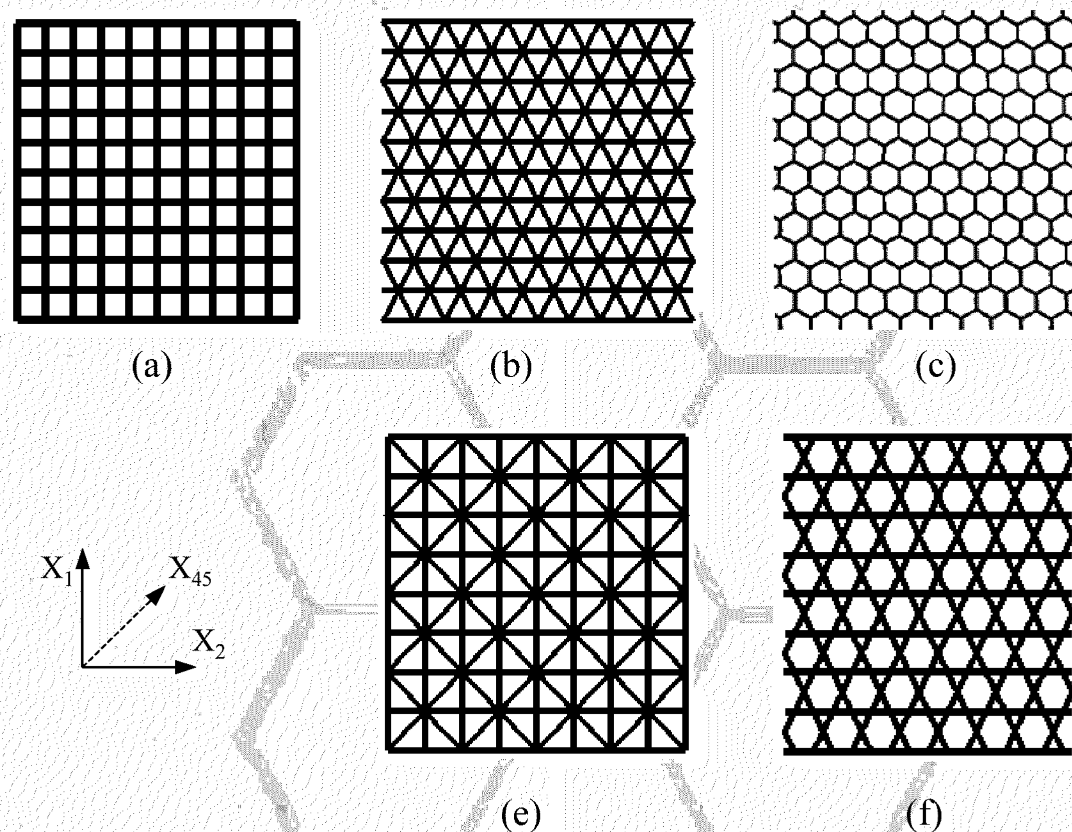
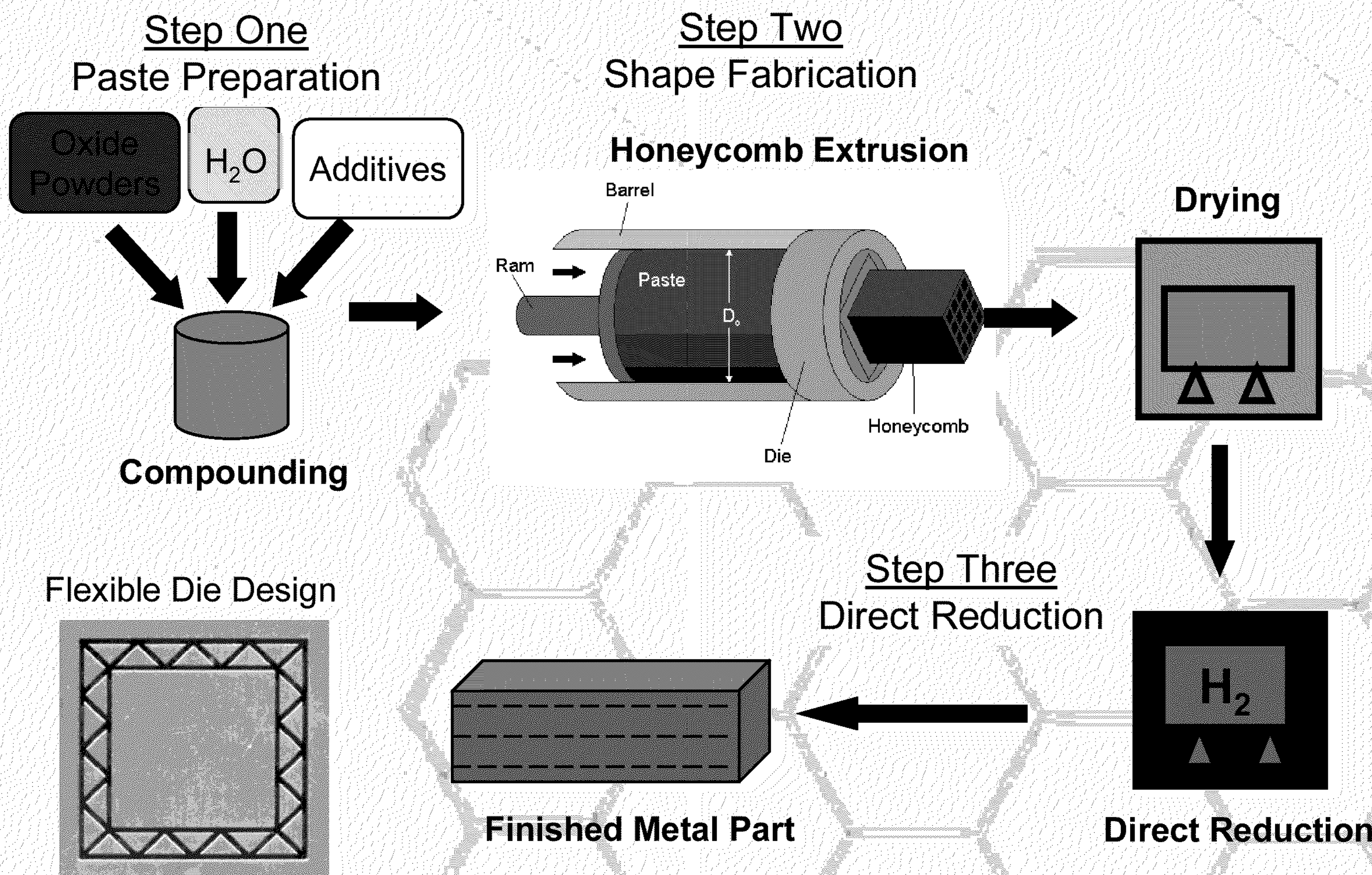
Honeycombs with Various Cell Types



(a) square; (b) triangle; (c) hexagonal; (d) mixed triangle and square; (e) kagome

Oxide Powders Transformed into Metal Linear Cell Structures



Material Compositions

Maraging Steels

Fe 18Ni 12Co 4Mo 1.5 Ti

from Fe_3O_4, NiO, Co_3O_4 , MoO_3, TiH_2

Reduction = Hydrogen at 1350 °C

- **Ni Alloy - "617"**

  22Cr 55Ni 12Co 9Mo from Cr_2O_3 , NiO, Co_3O_4 , MoO_3

- **Copper**

  Cu, Cu 1Ni, Cu 3Ni, Cu 8Ni, Cu 3Ag from Cu_2O, NiO, AgO

- **Inconel reduction process ("718") ***

$$68NiO + 27.8Cr_2O_3 + 25.7Fe_2O_3 + 7.3Nb_2O_5 + 4.5MoO_3$$

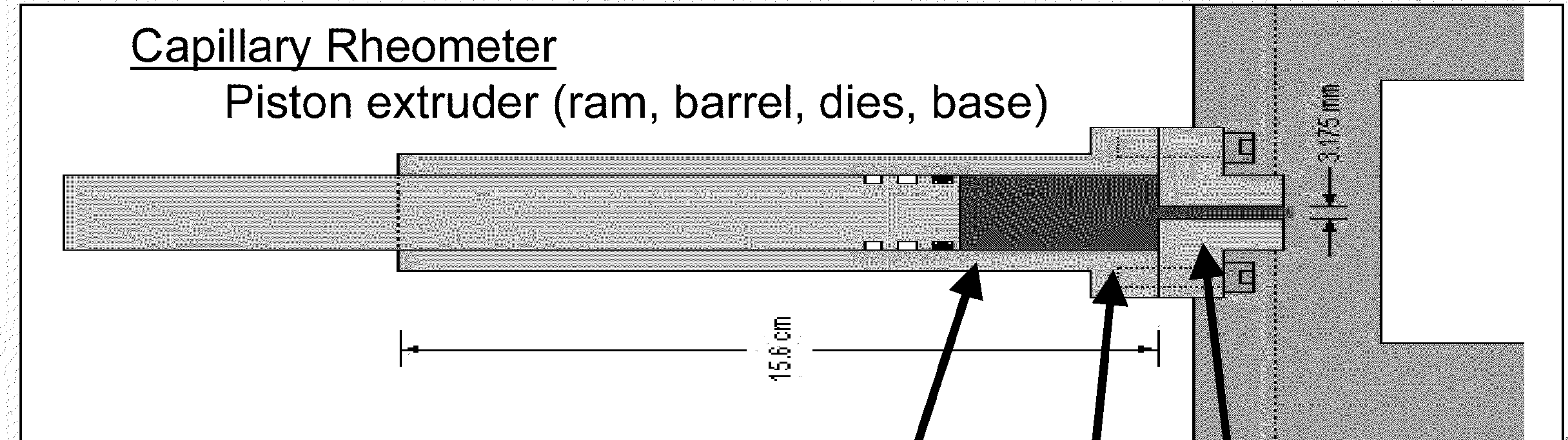
$$\xrightarrow{H_2} 53.4Ni\ 19Cr\ 18Fe\ 5.1Nb\ 3Mo + 34.8H_2O$$

*Weight Ratios

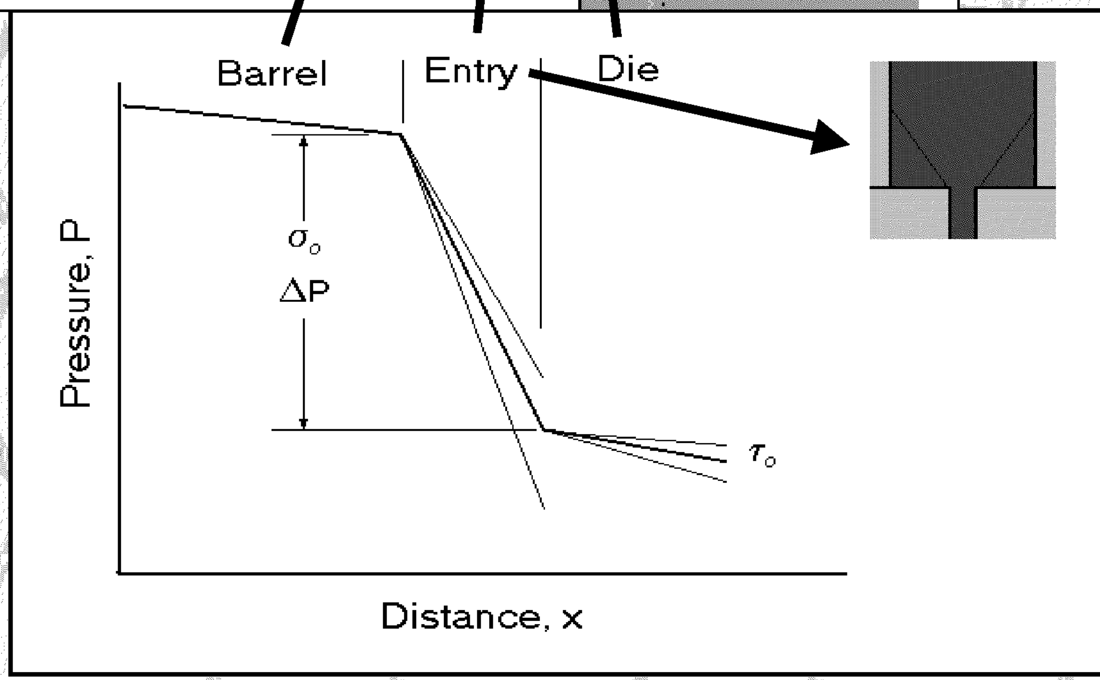
Paste Characterization

<u>Capillary Rheometer</u>

Piston extruder (ram, barrel, dies, base)



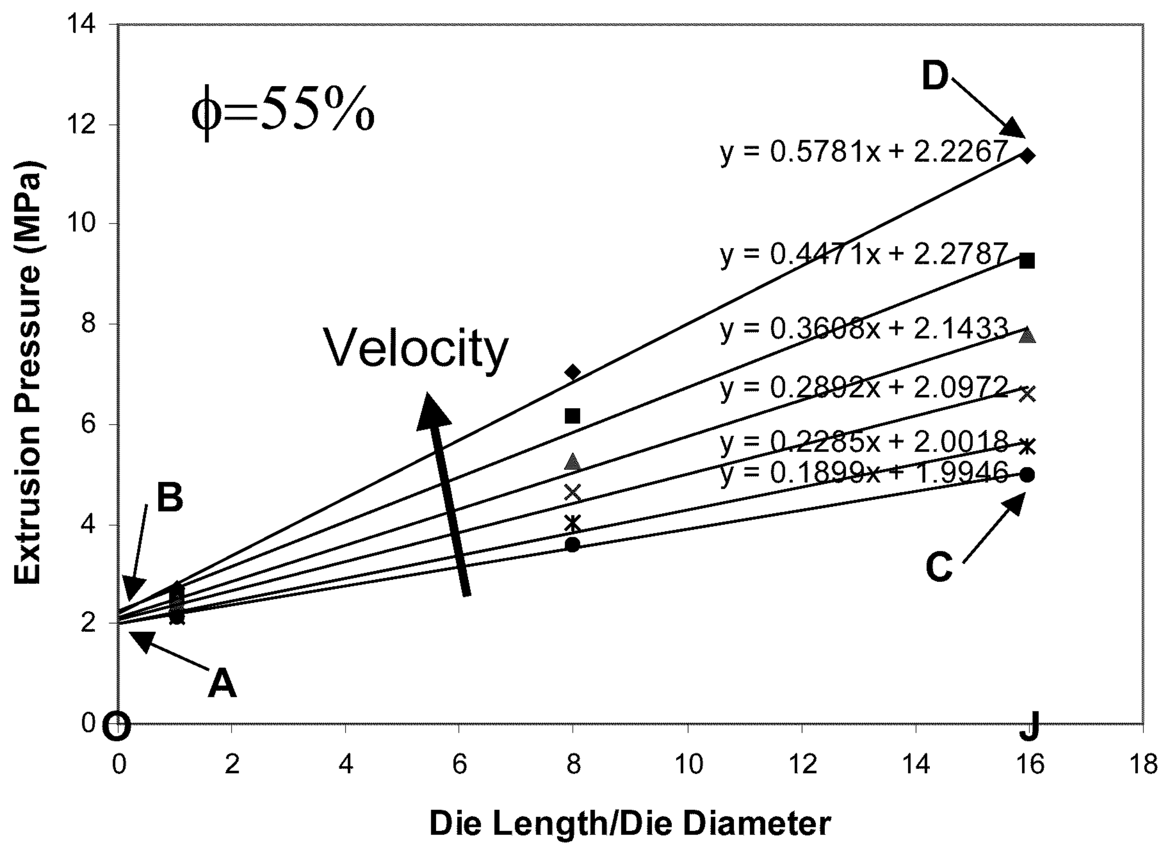
Pressure Distribution in Piston Extruder



Paste Characterization

Paste Yield Stress, σ_o, and Wall Shear Stress, τ_o.

$$P = 2(\sigma_o + \alpha V)\ln\left(\frac{D_o}{D}\right) + 4(\tau_o + \beta V)\left(\frac{L}{D}\right)$$



$$\sigma_o = \frac{(OA)}{2\ln\left(\frac{D_o}{D}\right)}$$

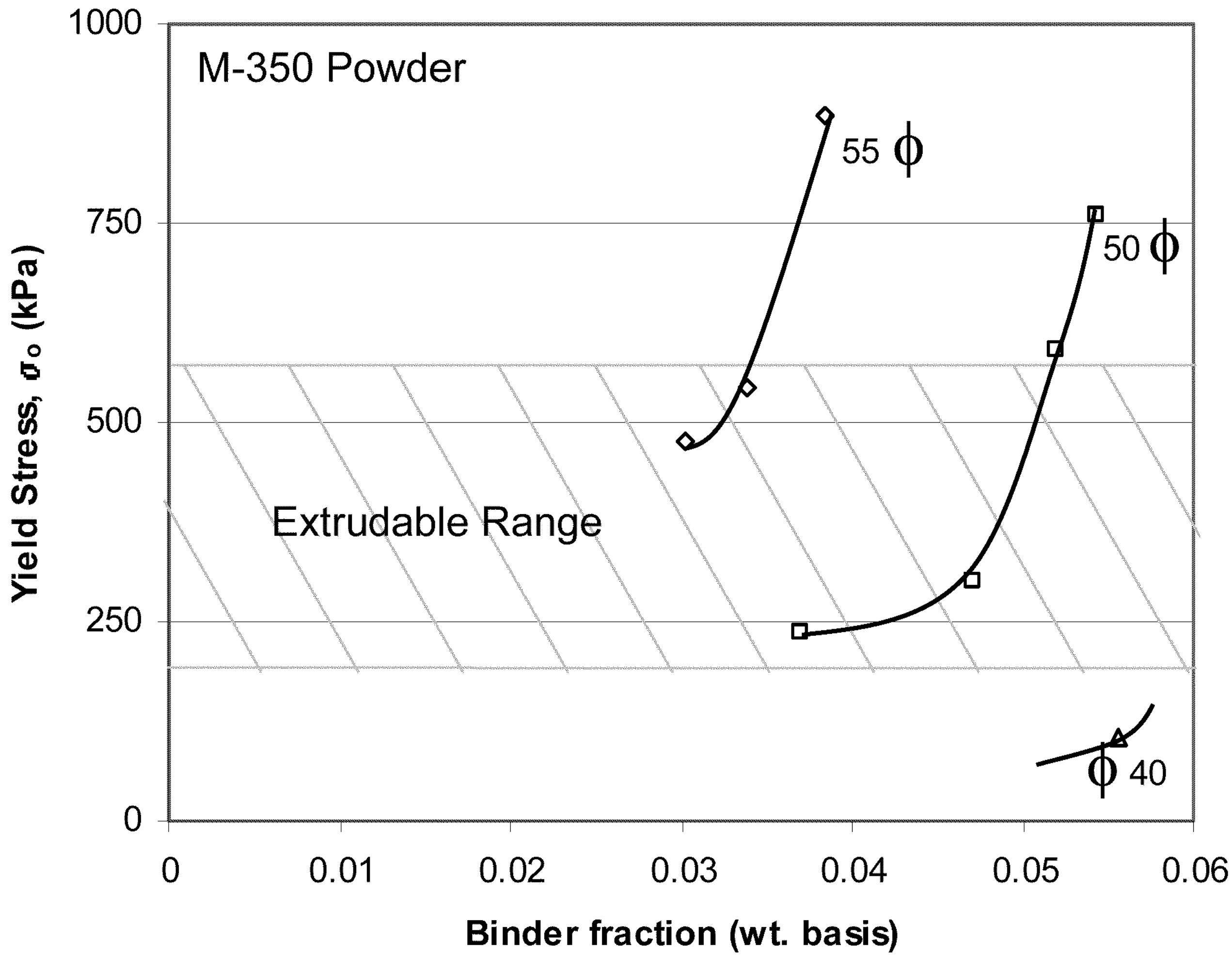
$$\tau_o = \frac{(CJ) - (OA)}{4(OJ)}$$

After Benbow
and Bridgewater

Paste Characterization

Effect of Binder and Solids Content, ϕ.

By varying binder and solids content, optimum plasticity coupled with minimum drying shrinkage and reasonable green strength can be achieved while keeping paste yield strength in the extrudable range.



Linear Cellular Die Design

- Extrusion pressure is dependent on:
  - Extrudate velocity
  - Paste rheology

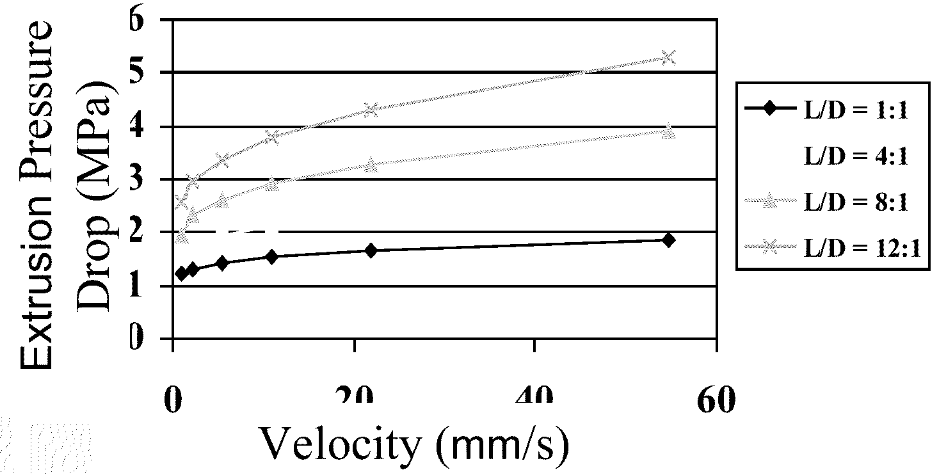
- Pressure drops result from:
  - Change in die area

$$P = (\sigma_o + \alpha V)\ln(A_o / A)$$

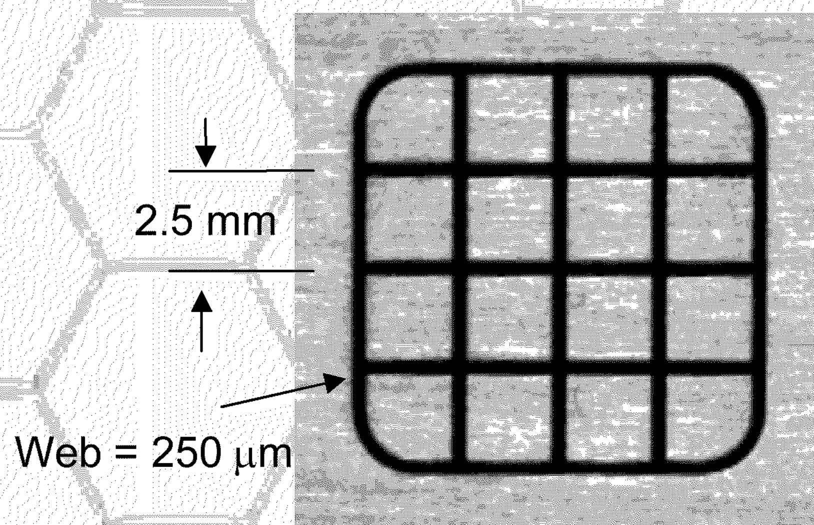
  - Shear stresses from die wall

$$P = (\tau_o + \beta V)(ML / A)$$

- Utilizing these relationships, predictions for pressure drops across honeycomb dies can be made.



Honeycomb die for rheometer:



Linear Cellular Die Design

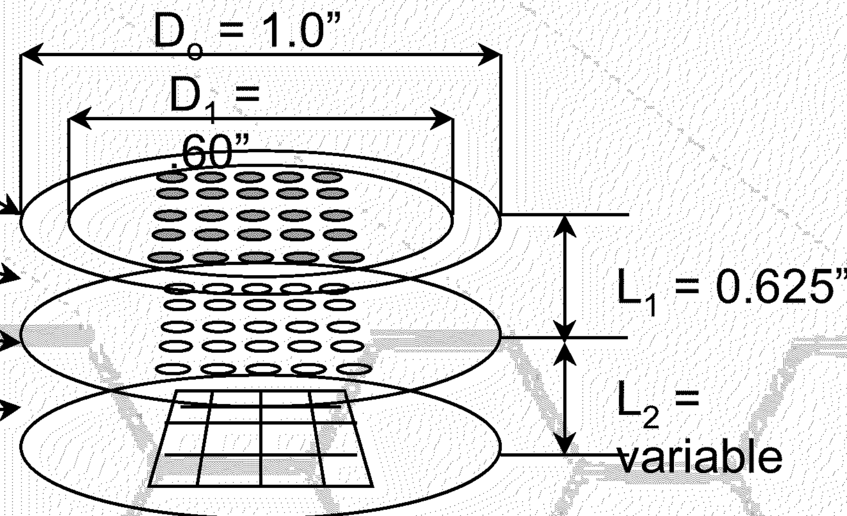
Square Cell Die Parameters/ Pressure Drop Modeling

P_1 = pressure drop from area reduction in barrel to entry holes

P_2 = pressure drop from flow through holes

P_3 = pressure drop from area reduction in holes to slots

P_4 = pressure drop from flow through die slots



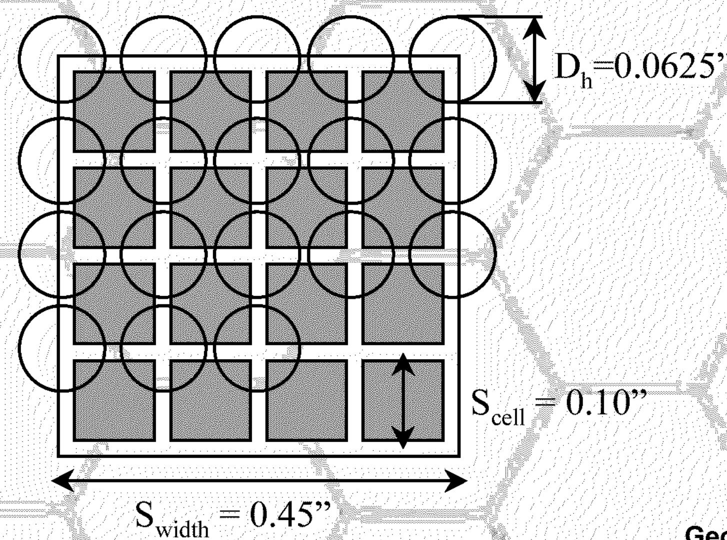
Blackburn & Böhm Equations

$$P_1 = 2(\sigma_o + \frac{\alpha 4Q}{\pi D_h^2}) + 2(\sigma_o + \frac{\alpha 4Q}{\pi D_h^2 N})\ln(\frac{D_1}{D_h\sqrt{N}})$$

$$P_2 = 4(\tau_o + \frac{\beta 4Q}{\pi D_h^2 N})(\frac{L}{D_h})$$

$$P_3 = (\sigma_o + \frac{\alpha Q}{A_s})\ln(\frac{A_h}{A_s})$$

$$P_4 = 4(\tau_o + \frac{\beta Q}{A_s})(\frac{M L_2}{A_s})$$



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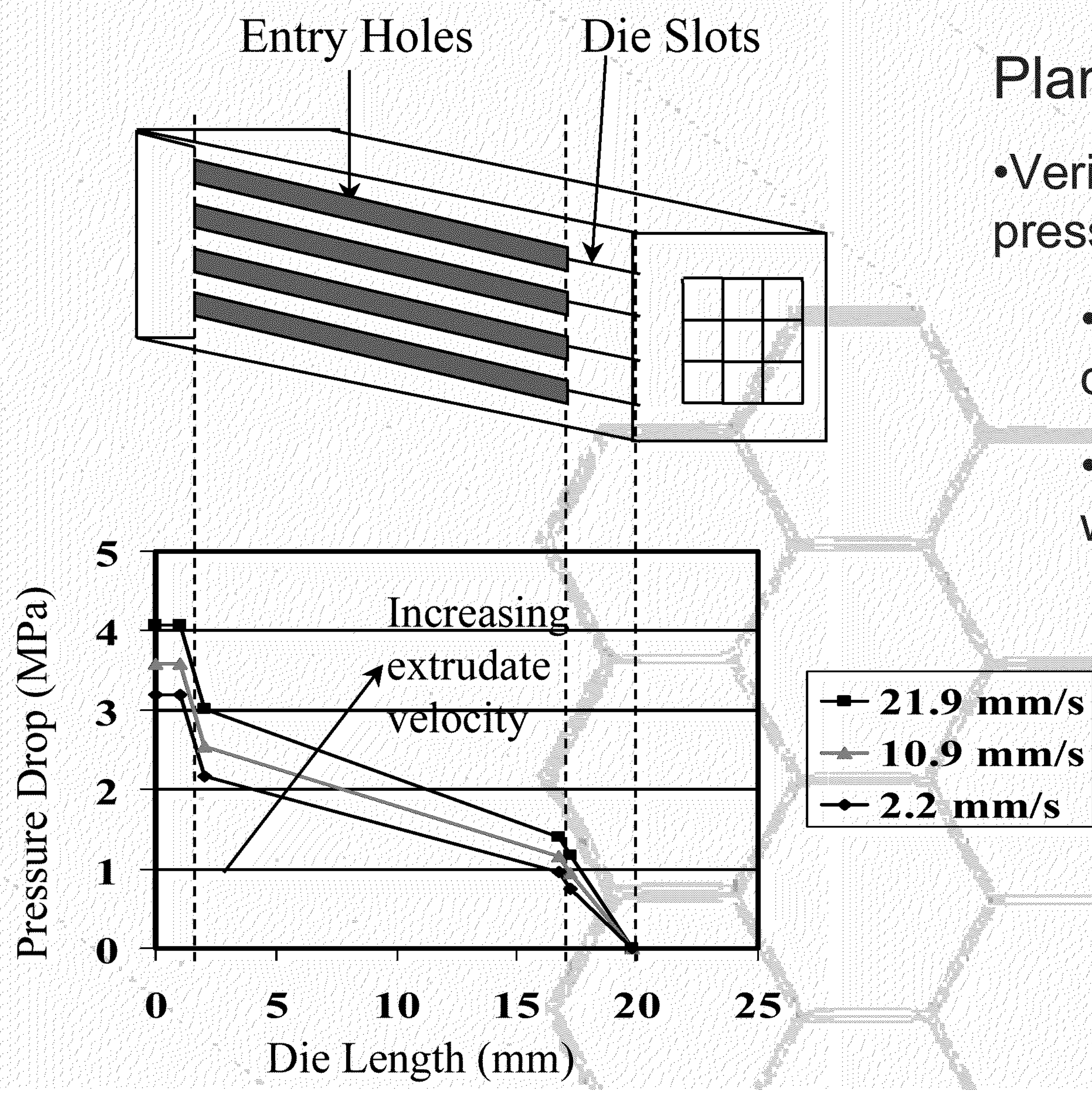
Linear Cellular Die Design

Projected Pressure Drops In Linear Cellular Dies



Planned Work:

- Verify linear cell die pressure drop model by:
  - Measuring pressure vs. die length
  - Measuring pressure vs. web thickness

Paste parameters:

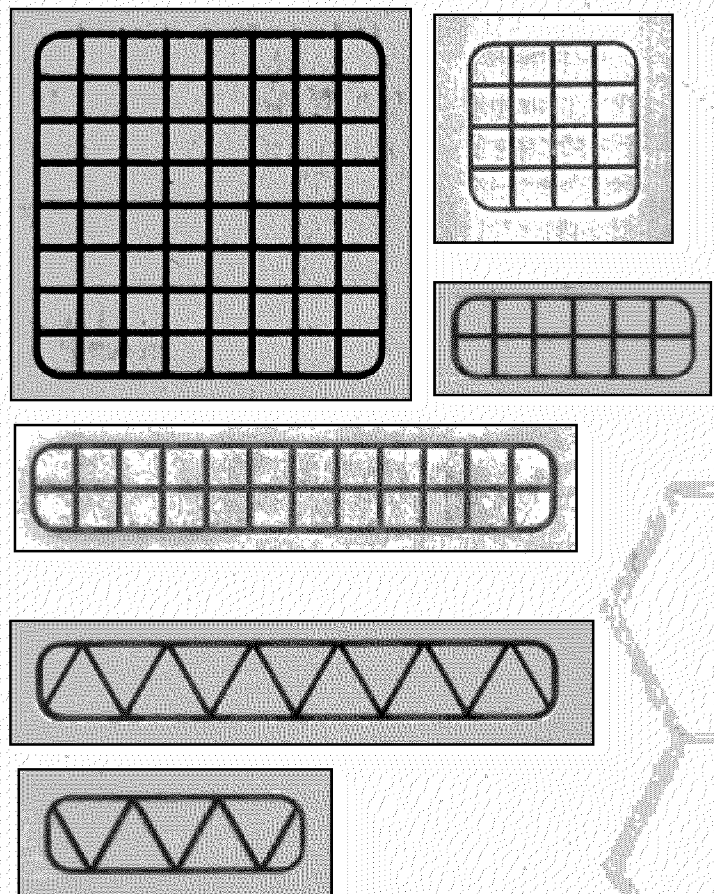
$\sigma_o = 0.3317$ MPa

$\tau_o = 0.0306$ MPa

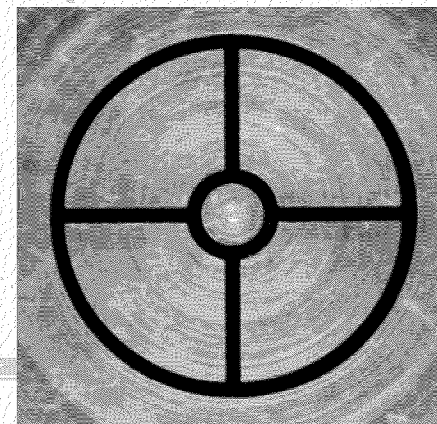
$\alpha = 0.00265$ MPa-s/mm

$\beta = 0.0009$ MPa-s/mm

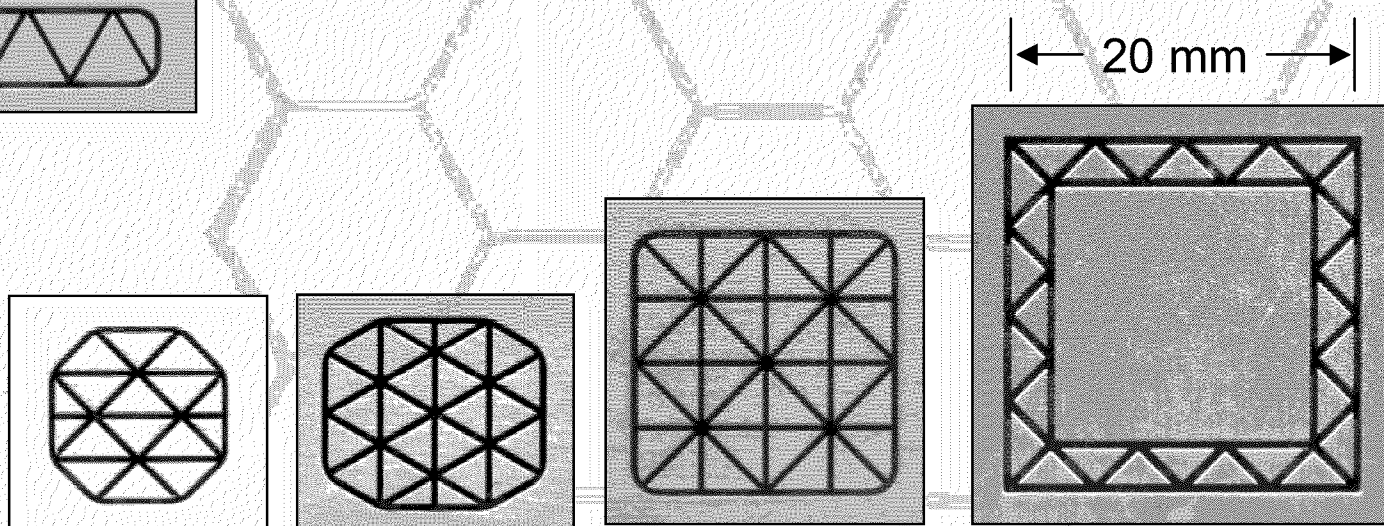
Linear Cell Extrusion Dies Designed at Georgia Tech



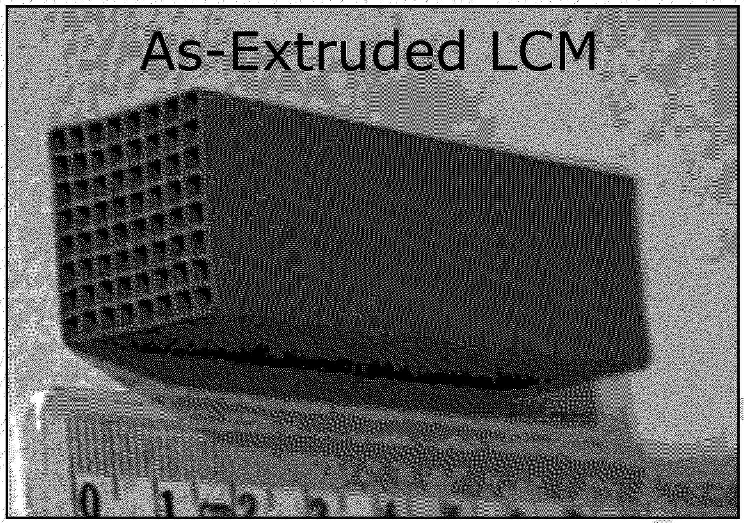
Cell Size = 2.5 mm
for Square Cells



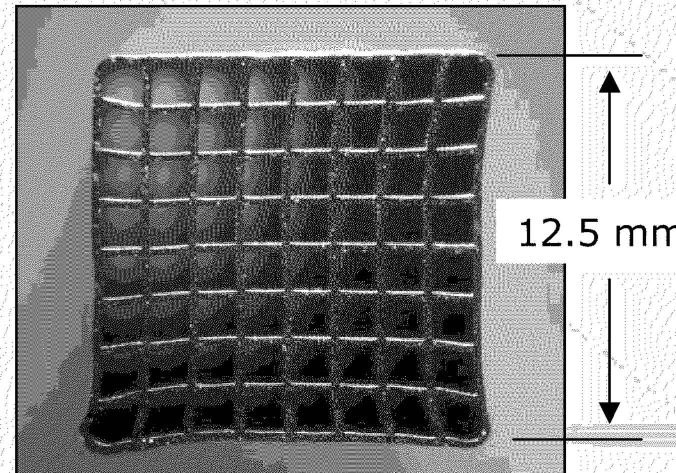
All Die Sizes Are Proportional

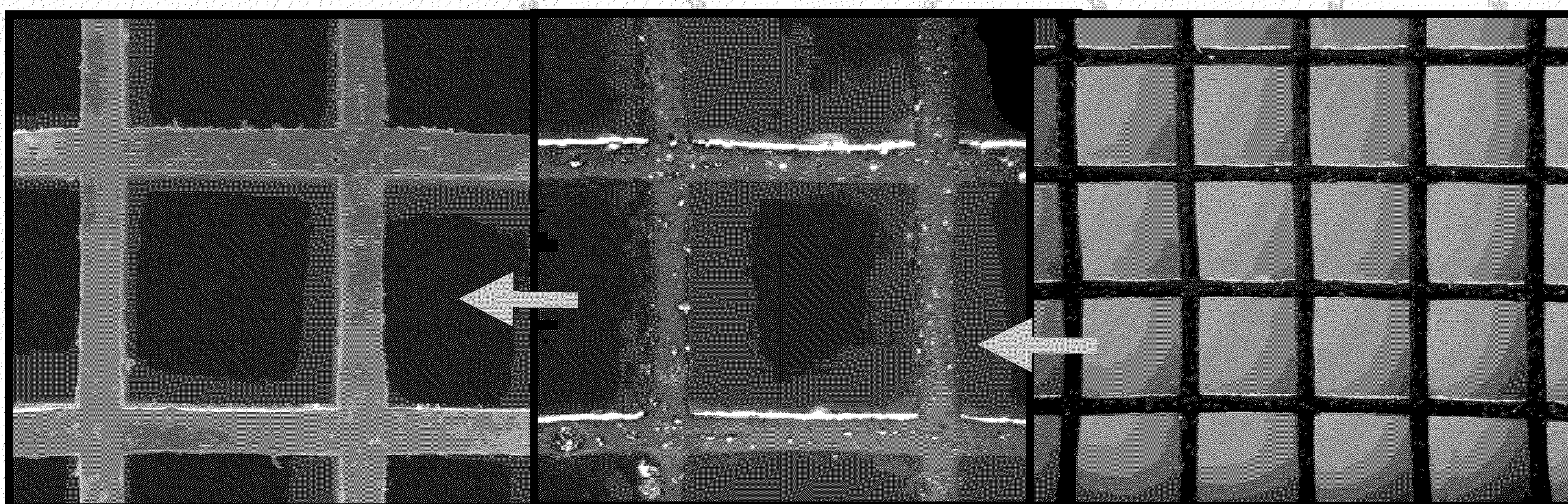


Square Cell, 8X8, Maraging Steel LCM



Reduction
& Sintering





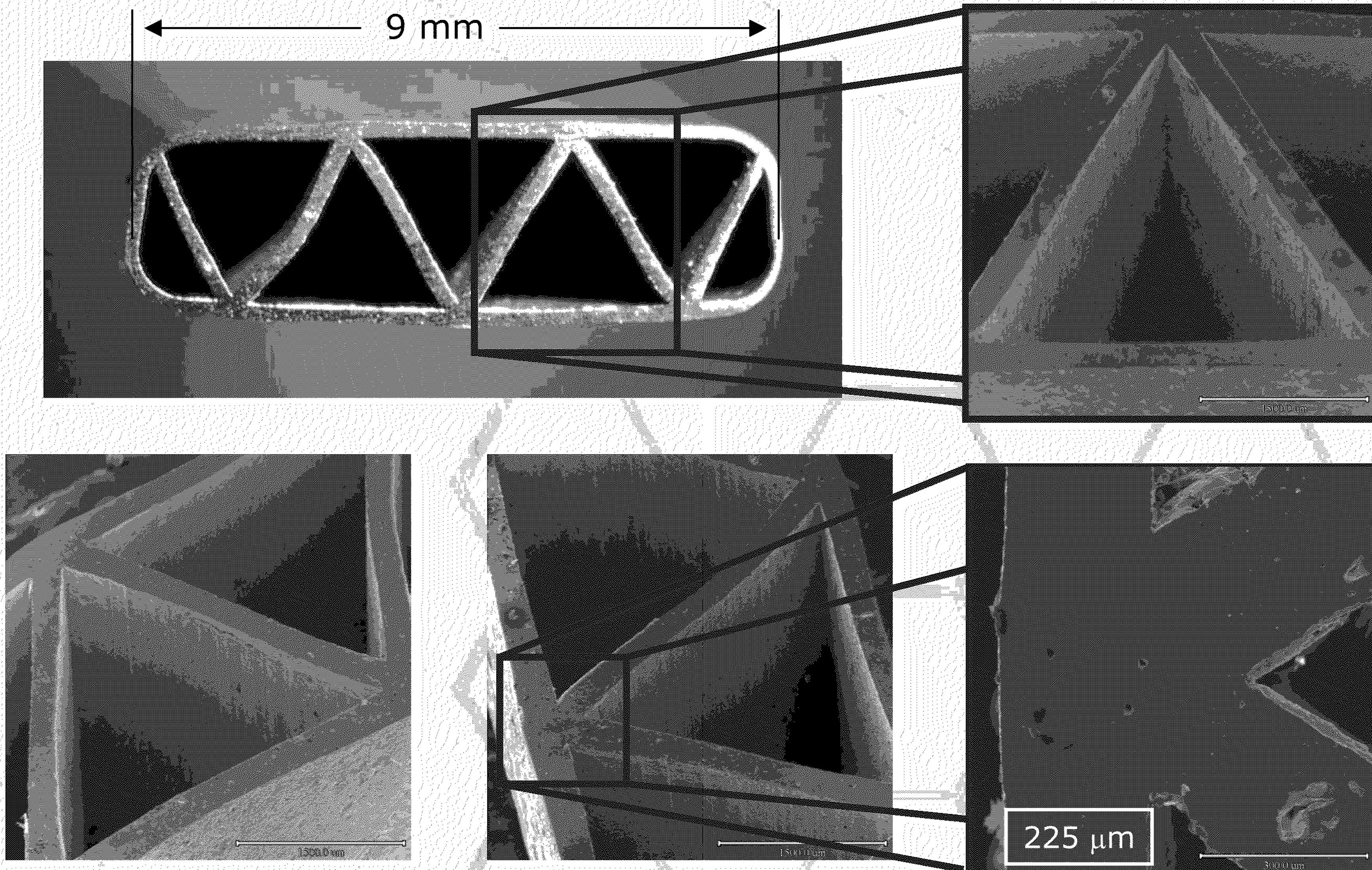
SEM Micrograph

Front Lighting

Back Lighting

Triangular Cell Extrusions

Maraging 200



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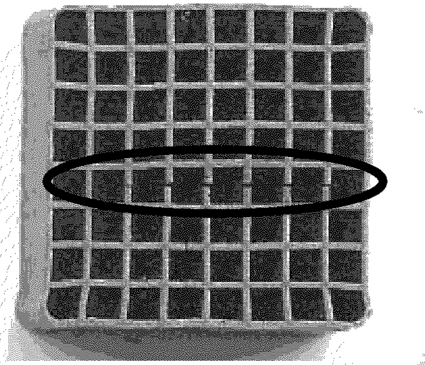
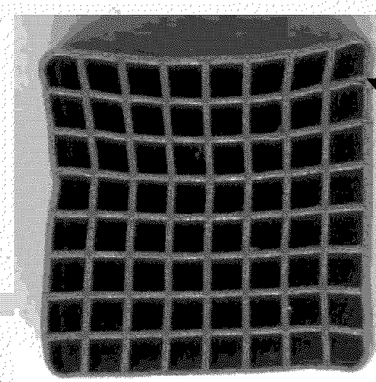
Compression Behavior of LCAs

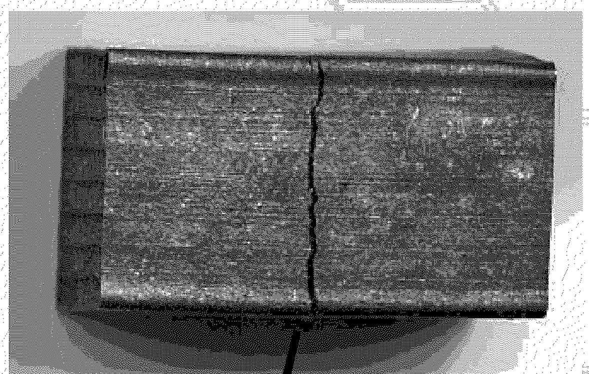
LCA Specimen Defects

Seam
Cracks

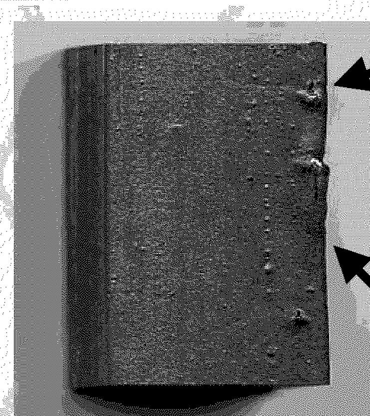




Skewed
Cells



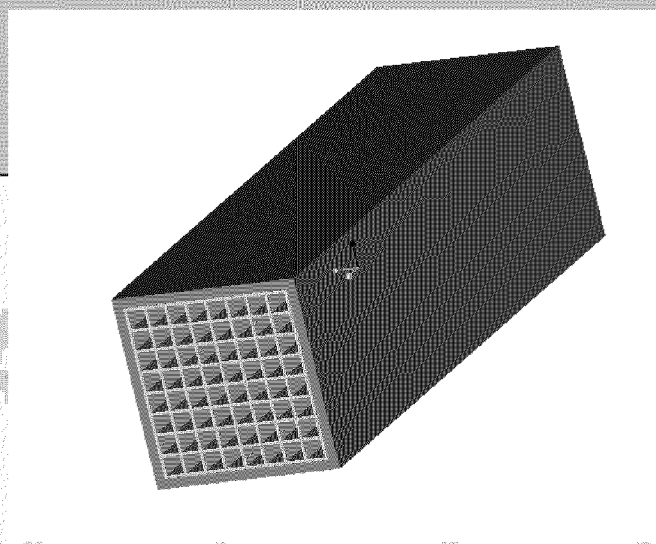
Drying Cracks



Surface
Imperfections

Curvature in
Extrusion
Process

LCMs as Heat Exchangers



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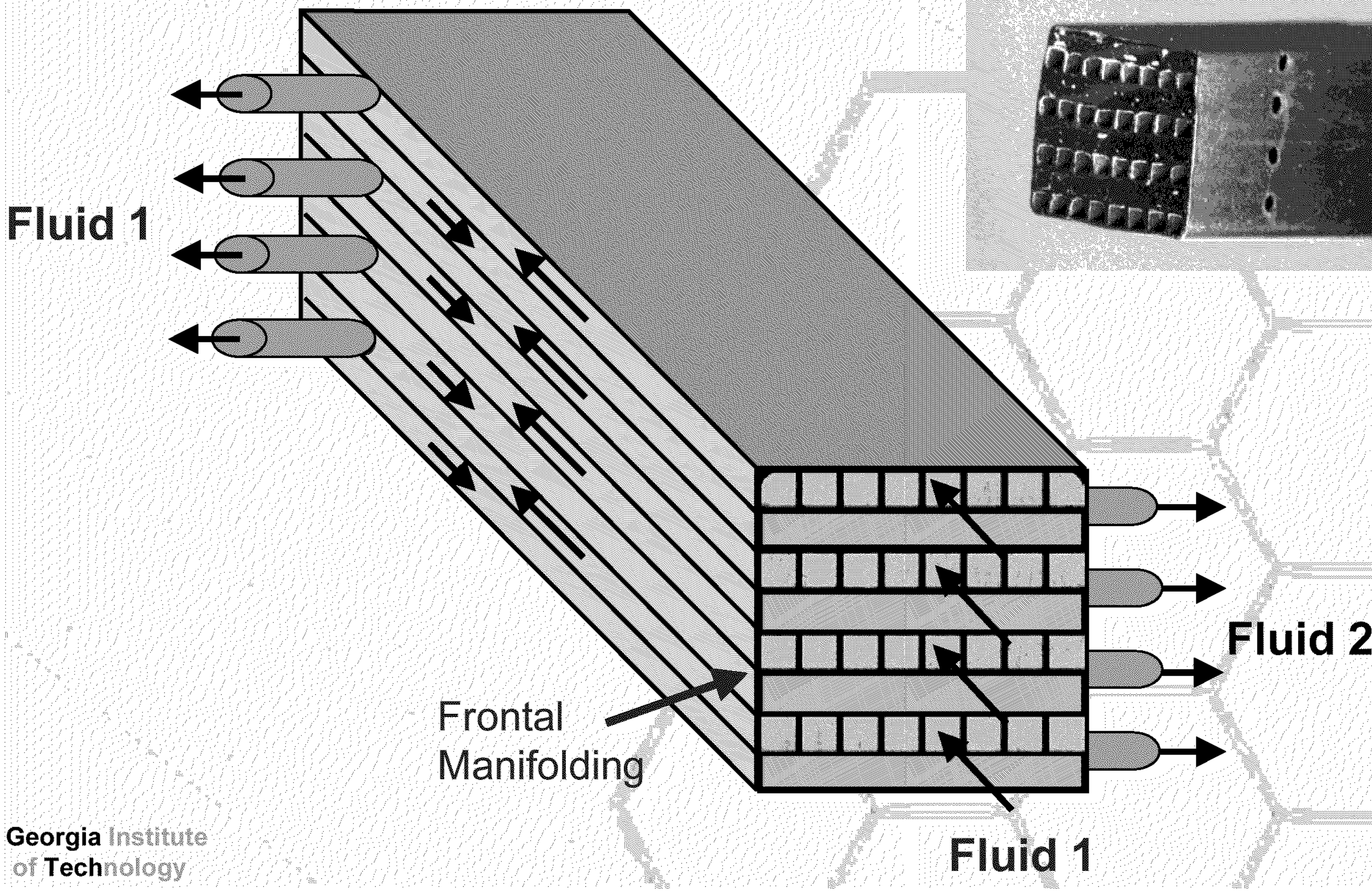
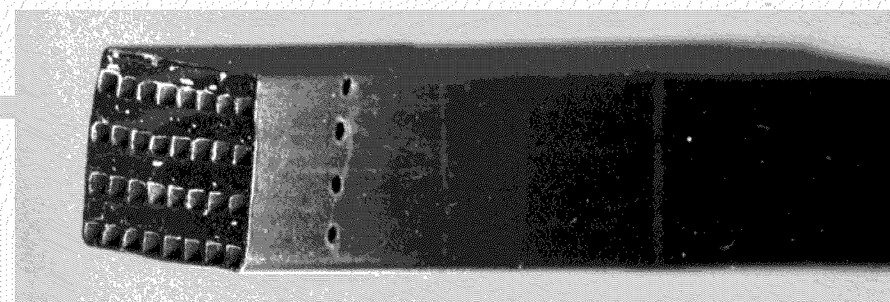
Counter Current Heat Exchanger

Counter current flow of two fluids on alternating rows is easily manifolded. When alternate rows of cells are plugged at one end and connecting holes are drilled in the same cells at the opposite end, flow paths are provided for fluid 1 on alternating rows. The opposite flow pattern is provided for fluid 2 by plugging opposite rows on the other end and drilling exit holes near the front face. This permits easily fabricated frontal manifolding for flow control.





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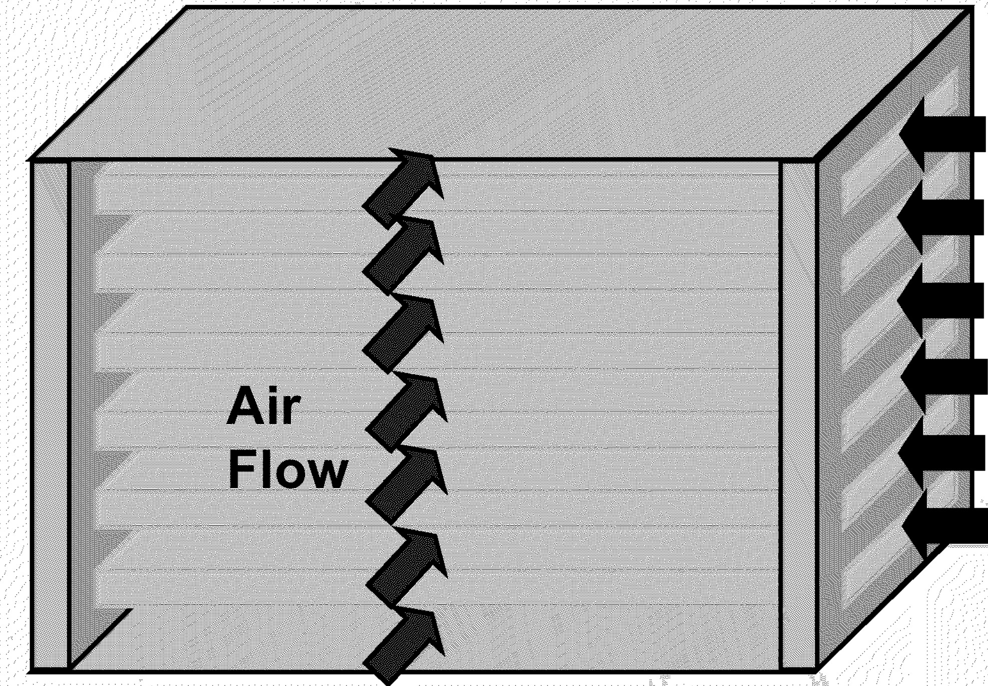
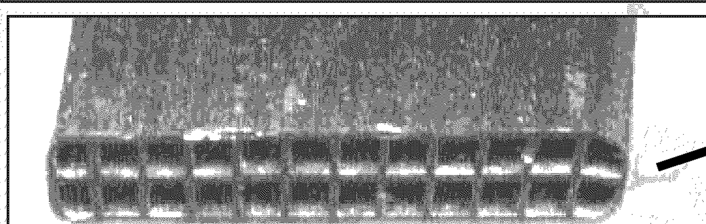
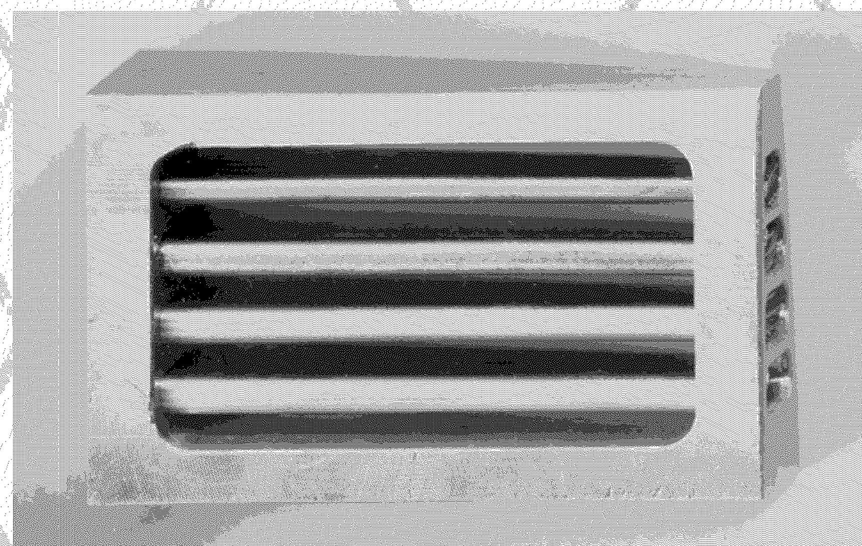
Northrop Grumman Prototype Heat Exchanger for Electronic Cooling



Square Cell Maraging Steel Channels

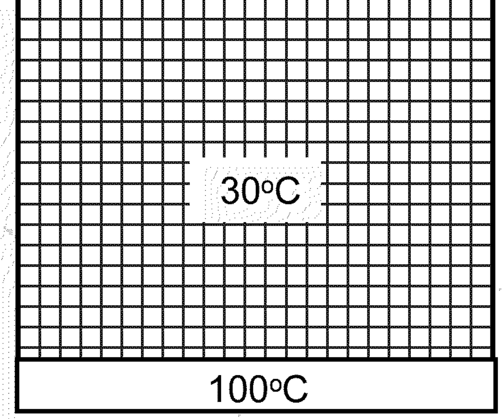


2 x 12 cell



Forced Air CPU Cooling - Design

Conditions:
50 X 64 mm inlet, 79 mm length
Input Air = 30°C, Spreader = 100°C
Max pressure Drop = 0.06 in. H_2O
Max Air Flow = 12 CFM
Cell Wall Conductivity = 165 W/m-K



<u>Ideal Isothermal</u>
Q(W), 365
R(°C/W), 0.19
J(W/cm^2), 92
T = 78 μm
C = 2.6 mm

Q(W), 286-317
R(°C/W), 0.24-0.22
J(W/cm^2), 72-79
T = 440 μm
C = 4.0 mm

Proprietary

Proprietary

Q(W), 306-340
R(°C/W), 0.23-0.21
J(W/cm^2), 79-72
T = 272 μm
C = 3.4 mm

Q(W), 324-350
R(°C/W), 0.22-0.20
J(W/cm^2), 81-88
T = 204 μm
C = 3.4 mm

Proprietary

Proprietary

Q(W), 332-354
R(°C/W), 0.21-0.20
J(W/cm^2), 83-89
T = 170 μm
C = 3.4 mm

Lower bound solution for optimized LCA geometry / Upper bound isothermal solution

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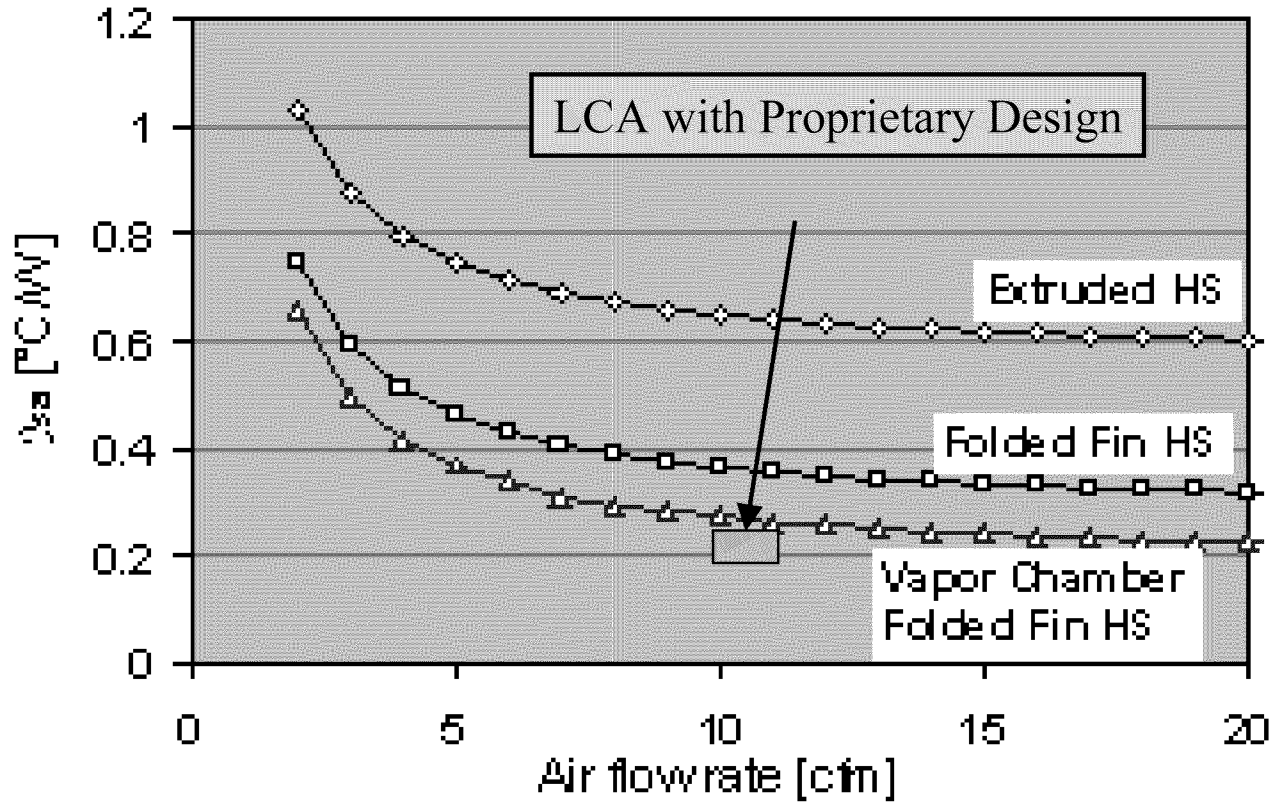
Forced Air CPU Cooling

Comparison of Thermal Cooling Solutions: Thermal Resistance vs. Flow Rate

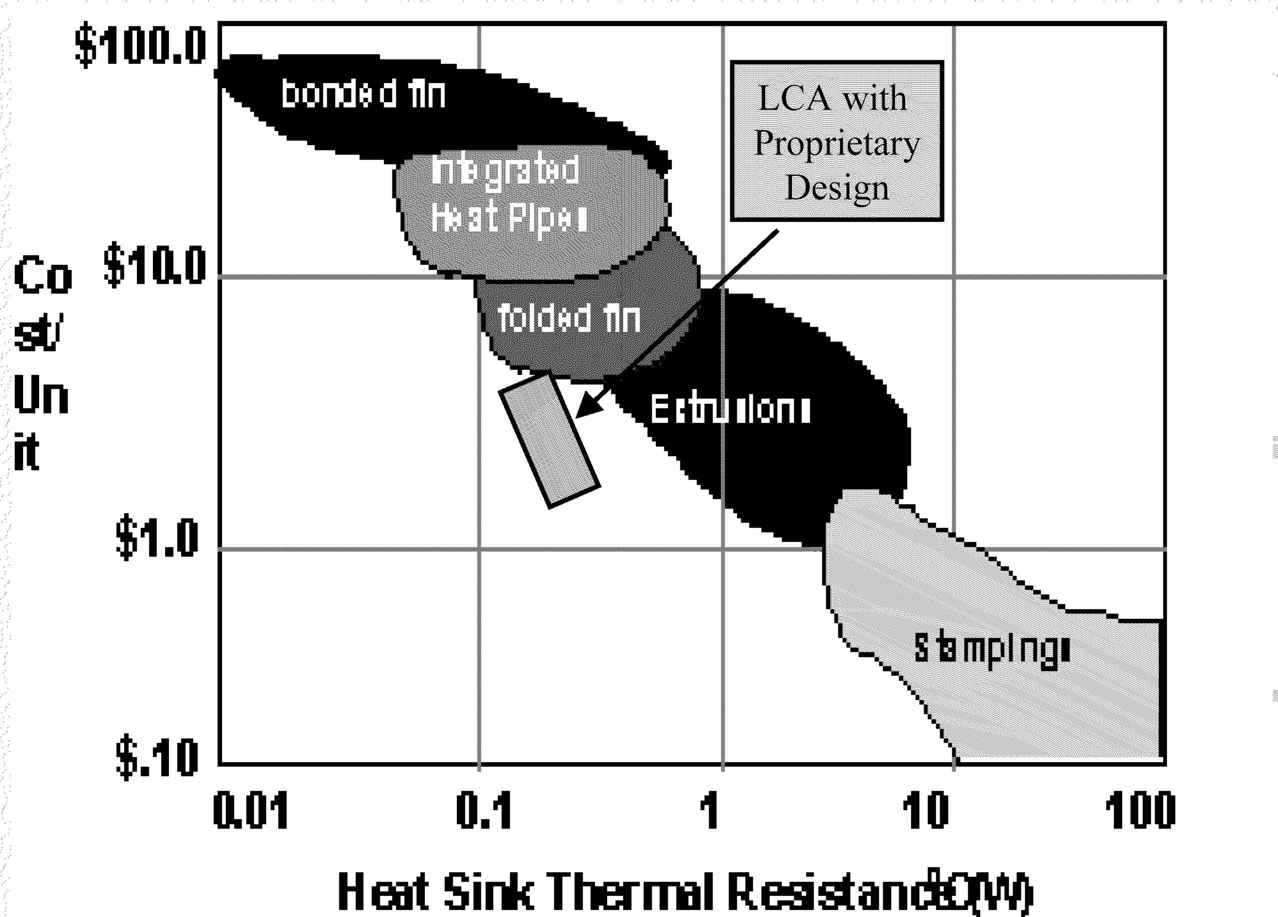


Original Source of Chart:
"Thermal Performance Challenges from Silicon to Systems",

R. Viswanath et al., Intel Technology Journal, 3Q 2000

Forced Air CPU Cooling

Comparison of Thermal Cooling Solutions:
Unit Cost vs. Thermal Resistance



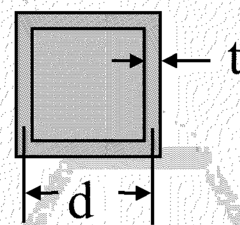
Original Source of Chart:
"Thermal Performance Challenges from Silicon to Systems",
R. Viswanath et al., Intel Technology Journal, 3Q 2000

Basic Issues - Heat Sinks

$$\alpha = \frac{\text{total surface area}}{\text{total volume}}$$

Simple for LCAs, controlled by die design, paste rheology, and processing limitations

e.g., square cells $\longrightarrow \alpha \approx \frac{4}{d}$ for small t/d.



$$\frac{\rho}{\rho_s} = \frac{2t}{d} - \left(\frac{t}{d}\right)^2 \approx \frac{2t}{d}$$ For low density

α values are much higher for same characteristic dimension of LCAs than for open cell foams

- Laminar (or transition) flow dominates for air cooling; simple pipe friction & heat transfer coefficient relations exist. Note: in porous media, transition occurs at Re in the 100-300 range - but this is not a classical random porous medium
- Can heat sink dissipate 50-100 W/cm^2 ?
- Strategies: (a) thermal gradients, (b) cell morphology, (c) hybrid heat sinks

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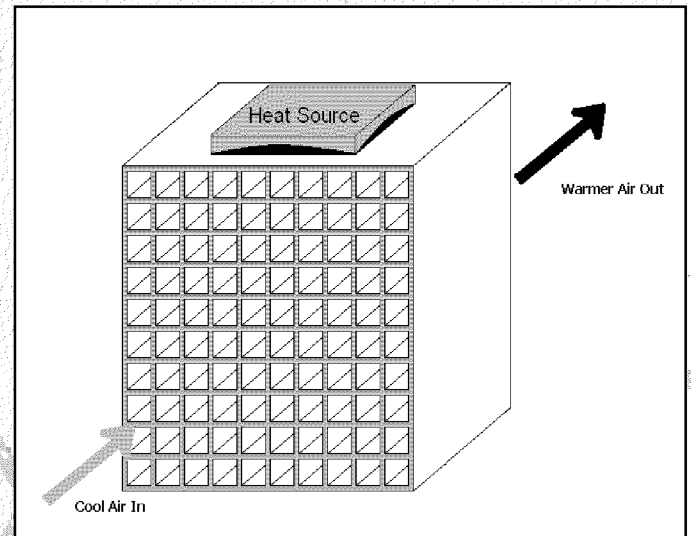
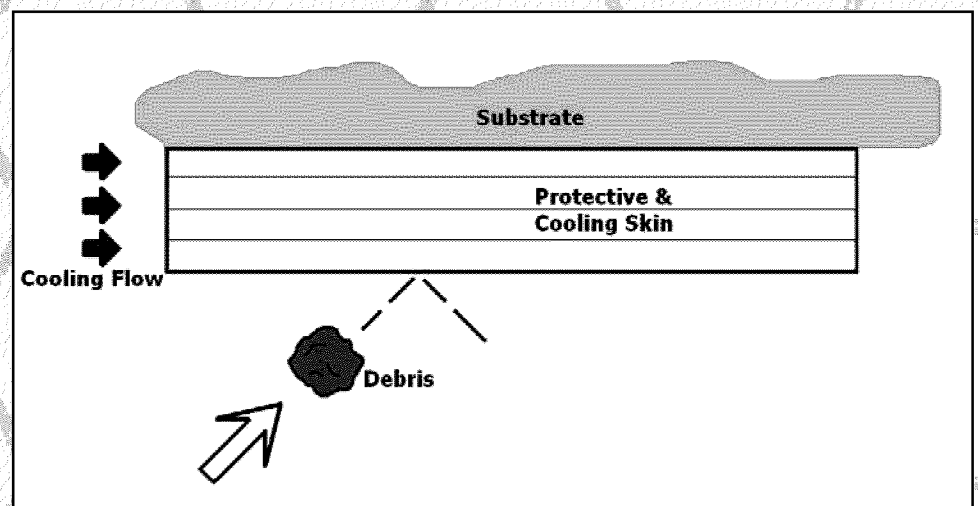
Some Applications

- Heat Removal
  - Computer chips
- Recapture of Lost Heat
  - Engines
- Structural / Heat Transfer
  - Actively cooled skins





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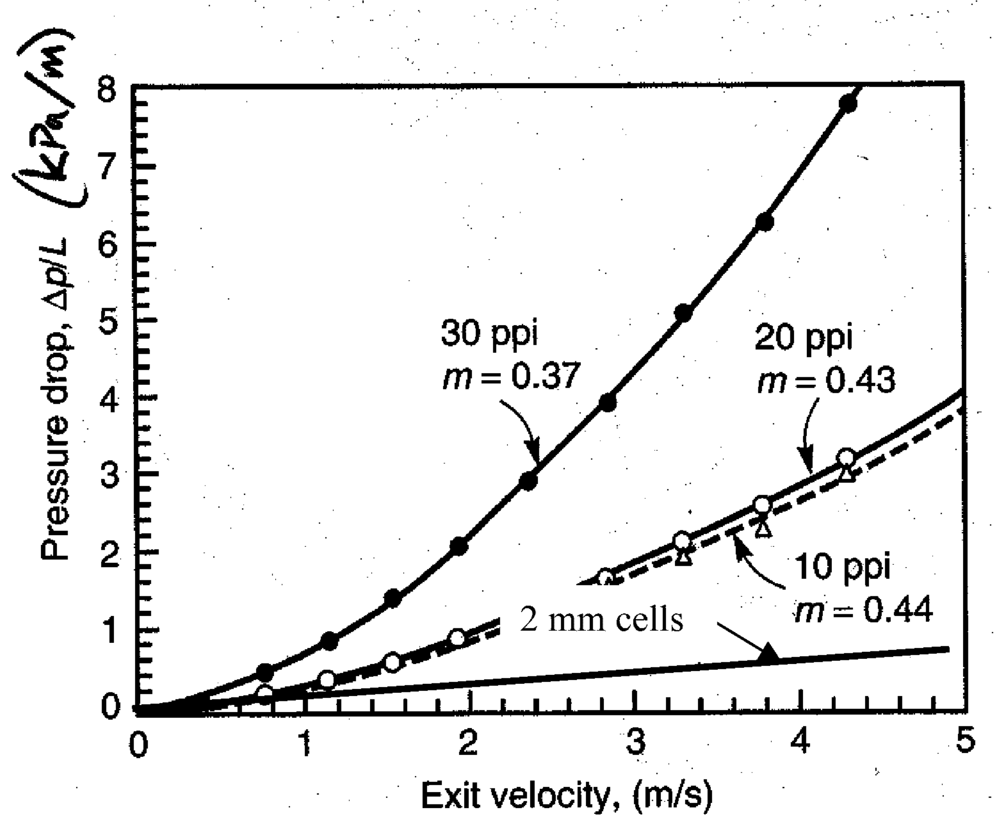
Laminar Flow Pressure Drop

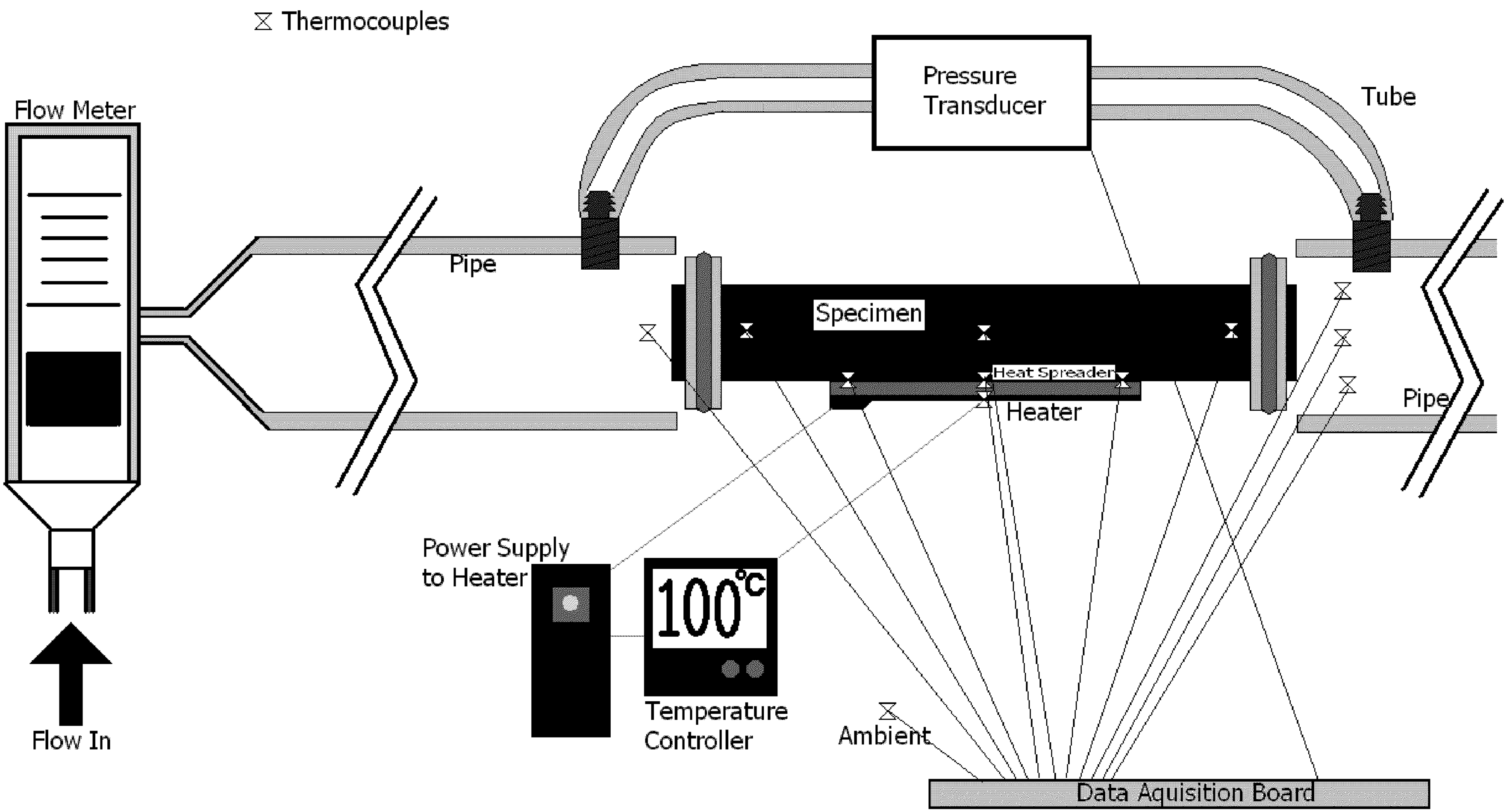


$$\frac{\Delta P}{\rho g} = f\,\frac{L}{d}\,\frac{V^2}{2g}, \quad Re = \frac{\rho V d}{\mu} = \frac{Vd}{\nu} \quad \text{(general relation)}$$

$$\frac{\Delta P}{\rho g} = f\,\frac{L}{d}\,\frac{V^2}{2g} = \frac{57}{Re}\,\frac{L}{d}\,\frac{V^2}{2g}, \quad \rightarrow \Delta P = \frac{28.5 \mu L V}{d^2}$$

laminar flow in square duct

Experimental Apparatus



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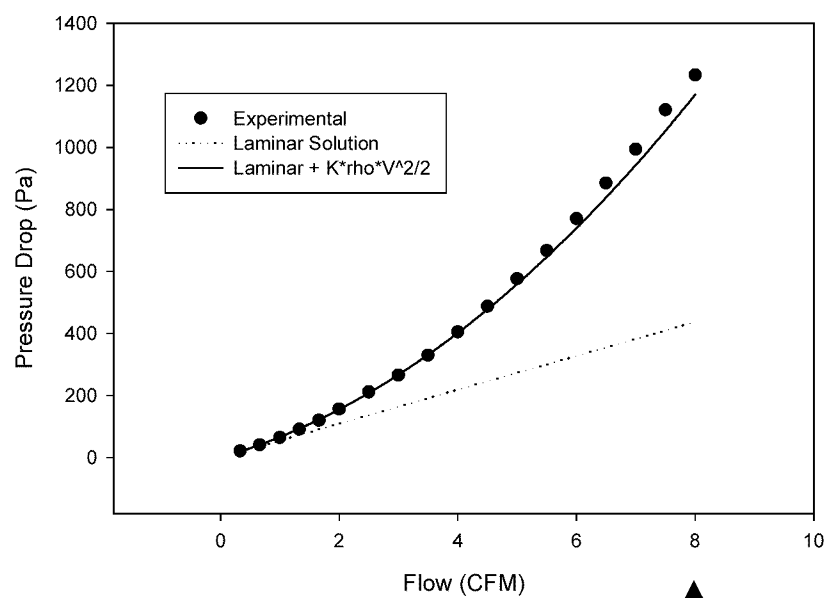
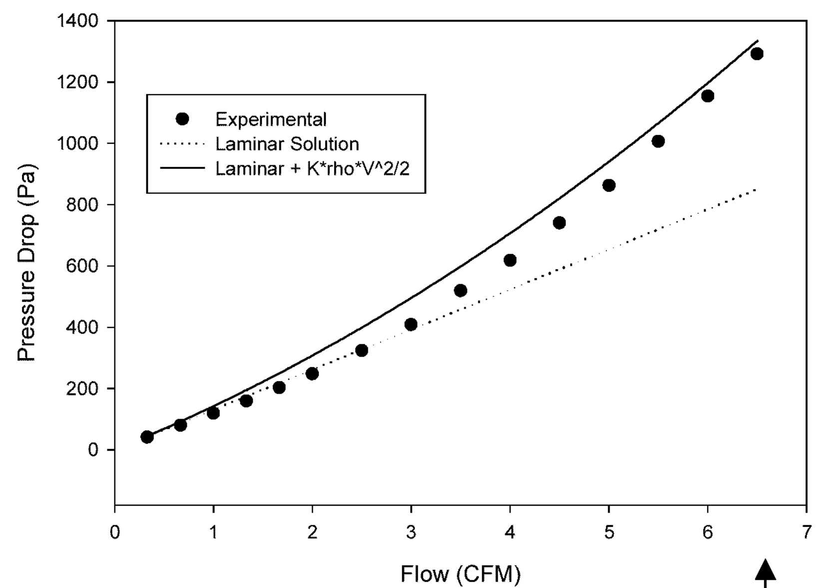
Pressure Drop vs. Flow and Head Loss
8x8 Maraging Steel LCA
Length = 4.36 cm, d = 1.35 mm, t = 0.23 mm
K = 1.2



$Re_d = 2400$

Pressure Drop vs. Flow and Head Loss
8x8 Maraging Steel LCA
Length = 11.2 cm, d = 1.37 mm, t = 0.25 mm
K = 1.2



$Re_d = 2000$

$$\Delta P_{LCA} = \Delta P\Big|_{laminar\,duct} + K\frac{\rho V^2}{2} = \Delta P\Big|_{load}$$

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Experiments: LCM Conductivity

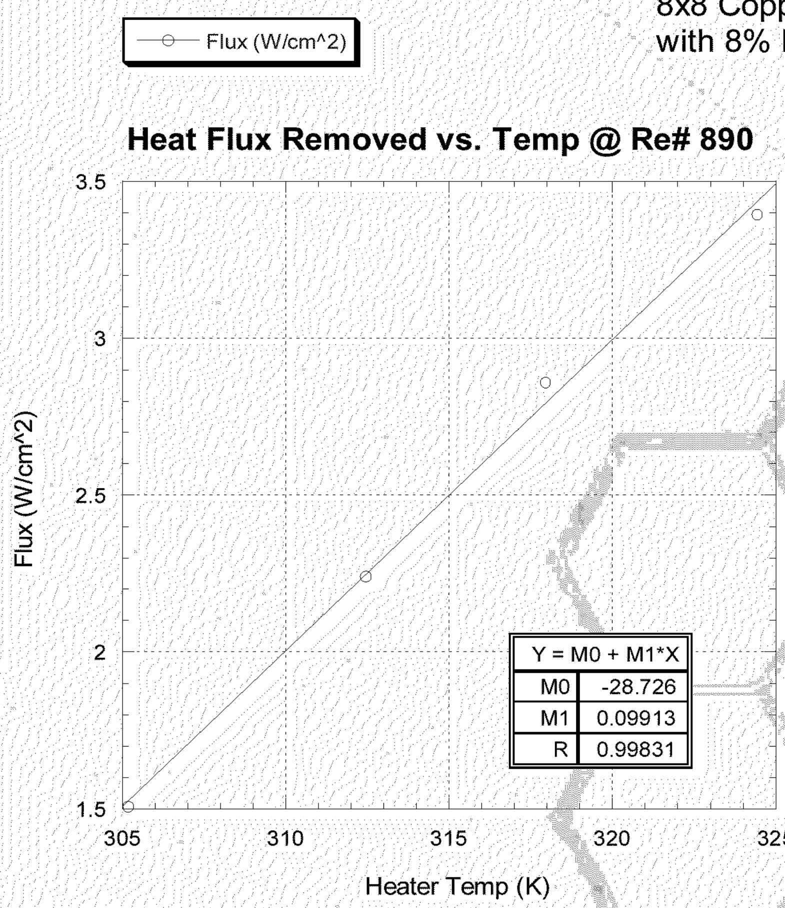
Composition (LCM)	Conductivity (W/m·K)
CuNi 8%	64.48
CuNi 3%	130.31
Cu	165.52
CuAg 1%	192.27
CuAg 3%	248.00

Tabular Values (Incropera & Dewitt, 1996)

Pure Copper	401
Commercial Bronze(90% Cu, 10% Al)	52
Constantan(55% Cu, 45% Ni)	23

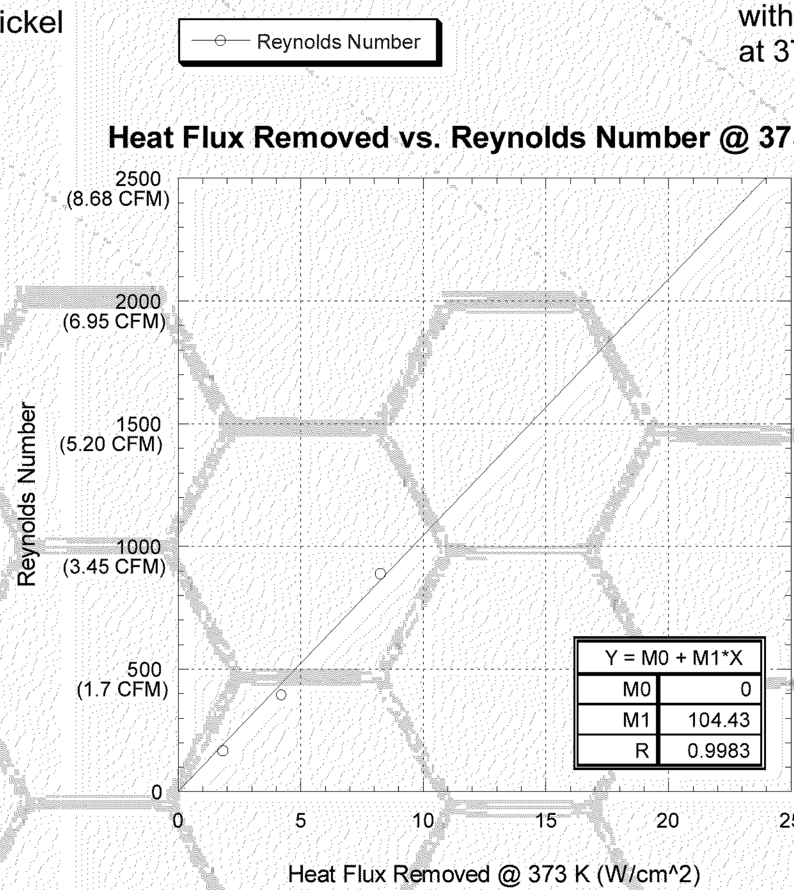
Experimental Results: 2" heated length

8x8 Copper
with 8% Nickel



Interpolation shows Flux =
8.25 W/cm^2 at 373 K

8x8 Copper
with heater
at 373 K



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pper and Lower Bound Solutions on Steady Sta Heat Transfer Rates for Square Cell LCMs

Upper:

$$q^{\text{isothermal}} = \rho C_p N d^2 V (T_b - T_\infty)\{1 - \exp(-\beta)\}$$

Lower:

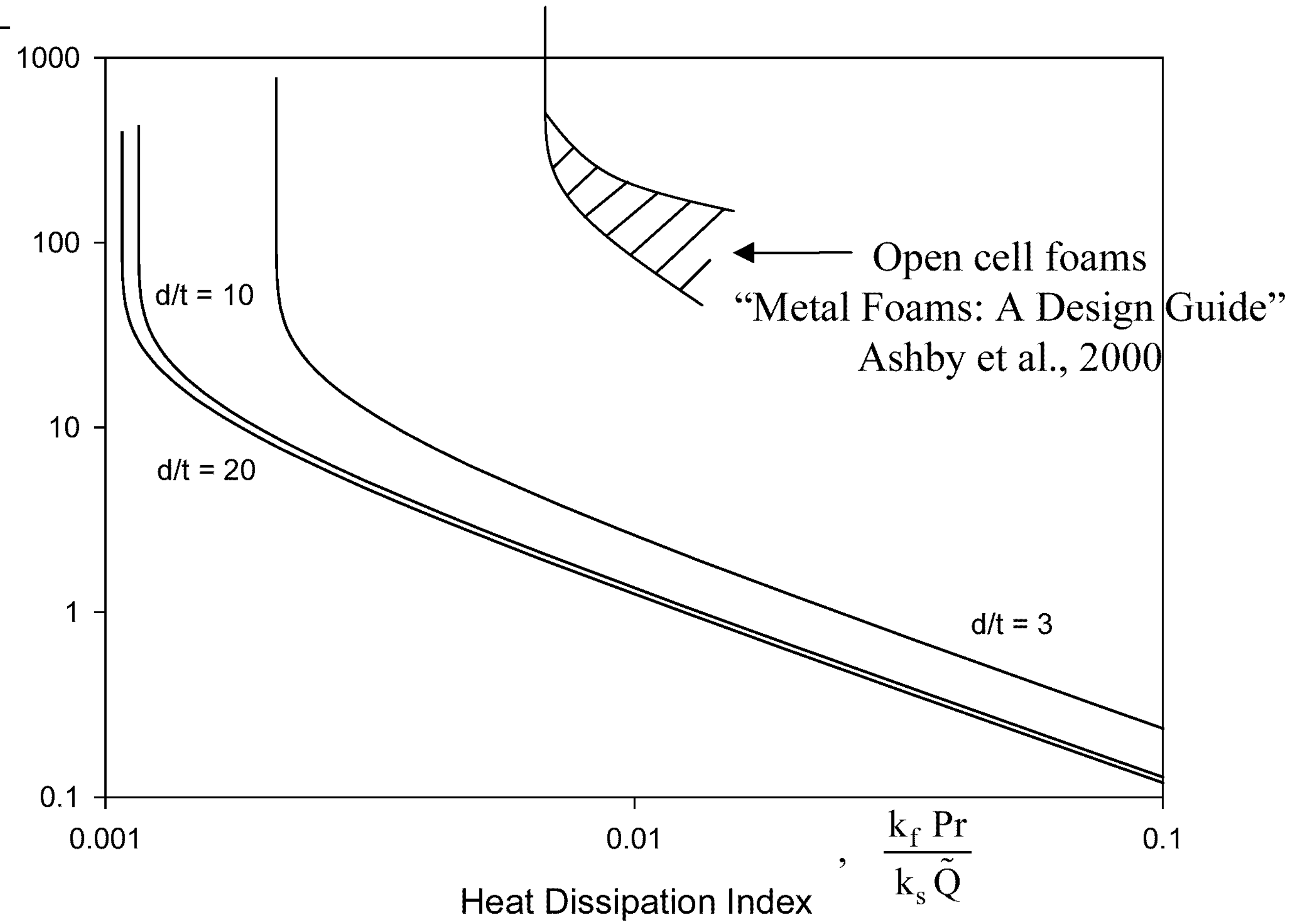
$$q^{\text{peripheral}} = \rho C_p N d^2 V (T_b - T_\infty)\{1 - \exp(-\beta)\}\sqrt{\frac{4}{LCM}}\tanh\left\{\sqrt{\frac{LCM}{4}}\right\}$$

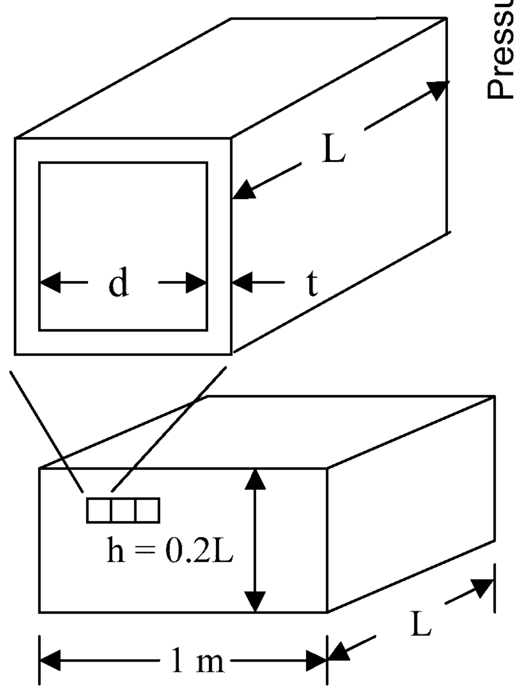
$$q^{\text{base}} = \rho C_p N d^2 V (T_b - T_\infty)\{1 - \exp(-\beta)\}\sqrt{\frac{1}{4LCM}}\tanh\left\{\sqrt{4LCM}\right\}$$

Comparison to Open Cell Metal Foams

$$Re_L = 5000 = \frac{\rho V L}{\mu} \quad \left(Re_d = \frac{\rho V d}{\mu}, \quad d \ll L \right) \qquad \tilde{Q} = \frac{\rho C_p N d^2 V (T_b - T_\infty)}{k_s (T_b - T_\infty)} \left\{ 1 - \exp\left(-\frac{4 Nu k_f L}{\rho d^2 V C_p} \right) \right\}$$

$$\tilde{P} = \frac{\Delta P V h L^2}{\rho \nu^3}$$





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Entry Length Effects for Square Cell LCMs

$$h = Nu\frac{k_f}{d}$$

$$Nu_{m,T} = 0.1222 + 2.8337\ln\left(\frac{1}{x^*}\right) - 0.8083\left\{\ln\left(\frac{1}{x^*}\right)\right\}^2 + 0.1134\left\{\ln\left(\frac{1}{x^*}\right)\right\}^3 \qquad x^* = \frac{x}{d\,Re\,Pr}$$

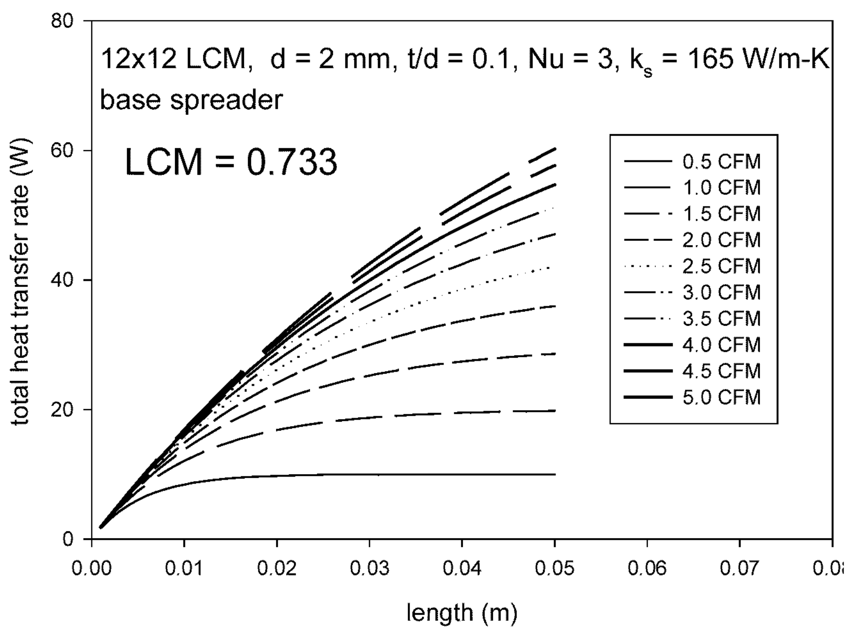
$$Nu_{ave} = \frac{1}{L}\int_0^L N_{m,T}\,dx = 2.0197 - 1.8975\ln\left(\frac{L}{d\,Re\,Pr}\right) - 0.4681\left\{\ln\left(\frac{L}{d\,Re\,Pr}\right)\right\}^2 - 0.1134\left\{\ln\left(\frac{L}{d\,Re\,Pr}\right)\right\}^3$$

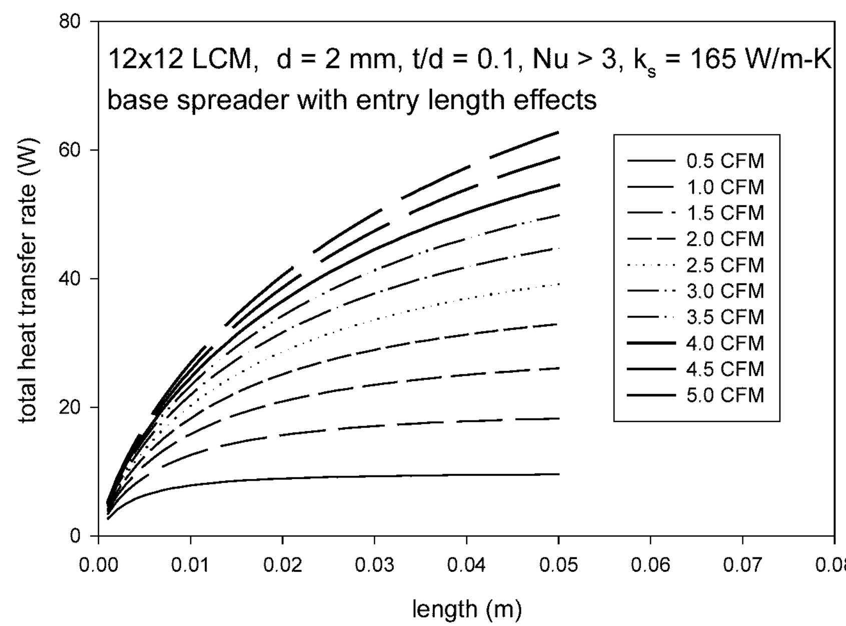
for $\frac{L}{d} \leq 0.21128\,Re\,Pr$

$$Nu_{ave} = 3 + 0.267\,Re\,Pr\frac{d}{L} \qquad \text{for } \frac{L}{d} > 0.21128\,Re\,Pr$$

"Advances in Heat Transfer: Laminar Flow Forced Convection in Ducts" by R.K. Shah and A.L. London, Academic Press, NY, 1978 (pg. 220).

Entry Length Effects for Square Cell LCMs





Max $Re_d = 450$

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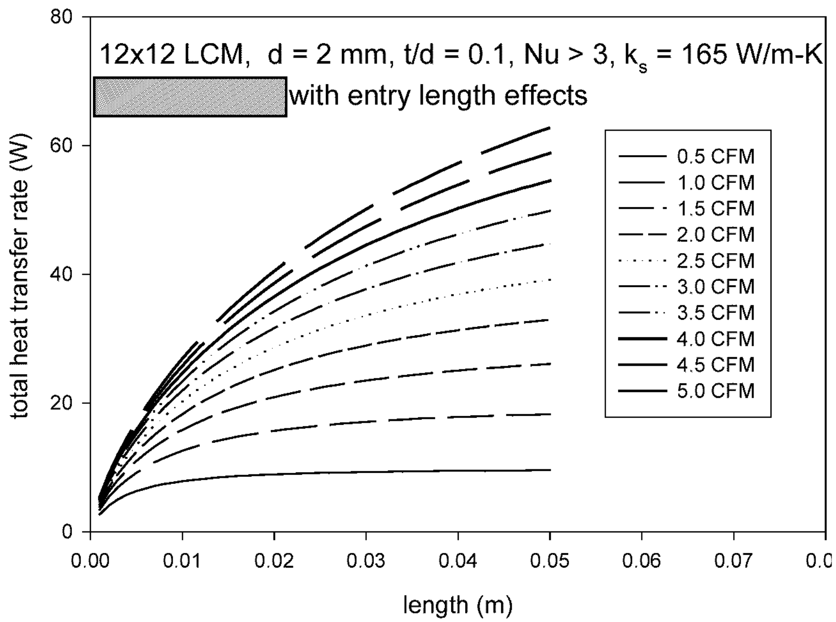
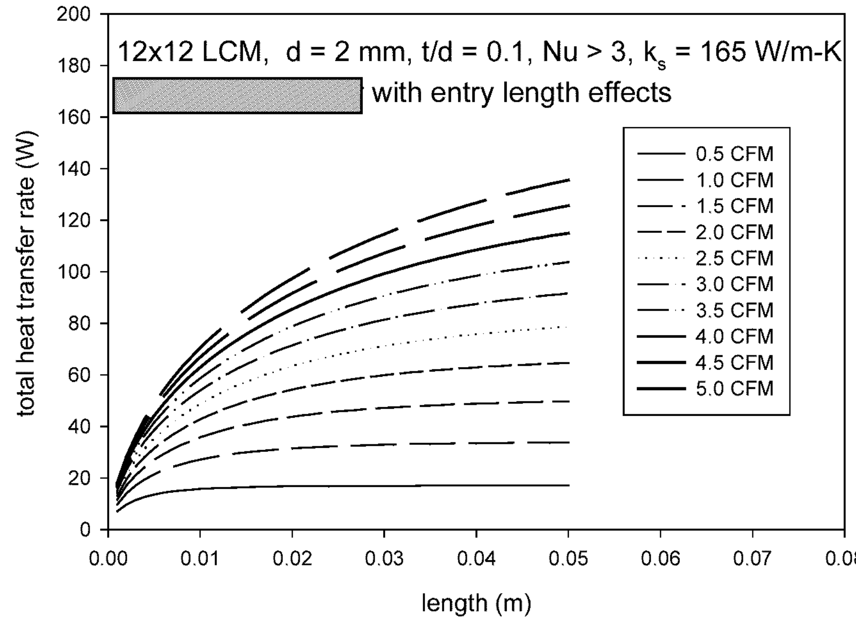
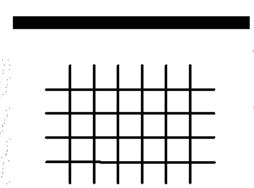
New Design Effects for Square Cell LCMs







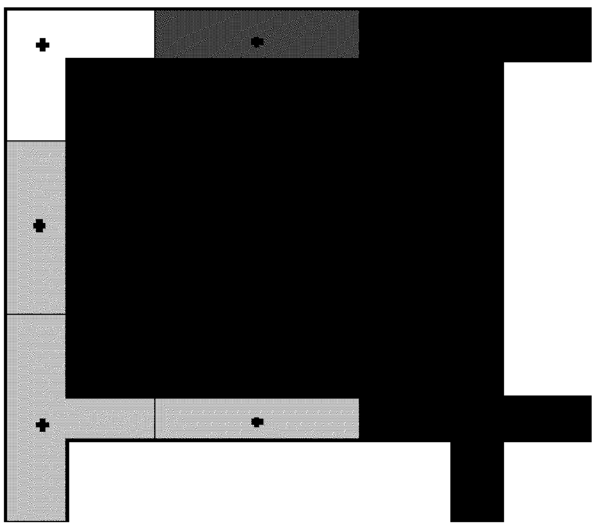
New Design

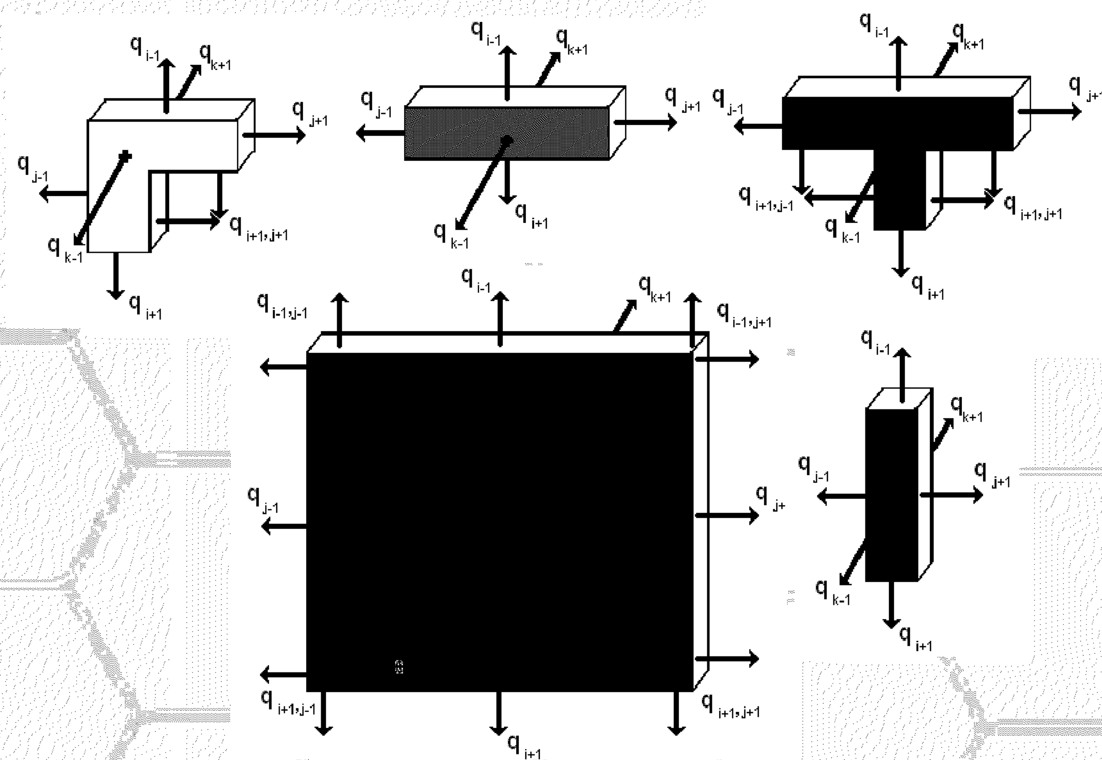
Max $Re_d = 450$

Finite Difference Code

- The following two equations are good for all of the different types of elements
  - $\dot{E}_{in} - \dot{E}_{out} + \dot{E}_{generated} = \dot{E}_{stored}$
  - $q_{i-1} + q_{i+1} + q_{j-1} + q_{j+1} + q_{k-1} + q_{k+1} = 0$
- Each element interacts with the elements around it by one of three methods of heat transfer
  - $Q = m \cdot c_p \cdot (T_{mean,out} - T_{mean,in})$
  - $Q = h \cdot A_c \cdot (T_{surface} - T_{fluid})$
  - $Q = - k \cdot A_c \cdot \Delta T / \Delta x$

Finite Difference Code





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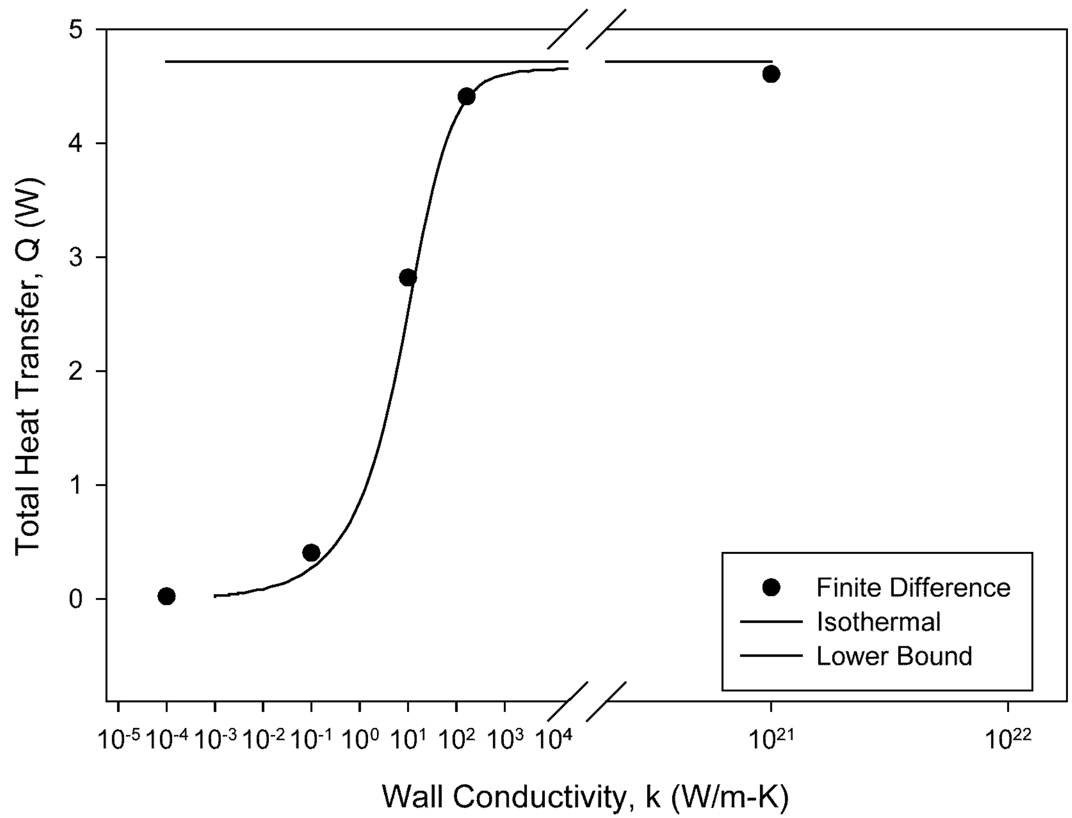
Effect of Conductivity

3x3, d=3mm, t=0.3mm
mass flow/cell = 3.59e-5 kg/s
Constant Temperature One Side
length = 0.02475 m
Nu = 3



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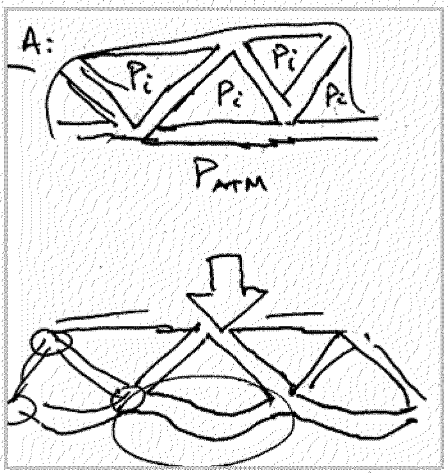
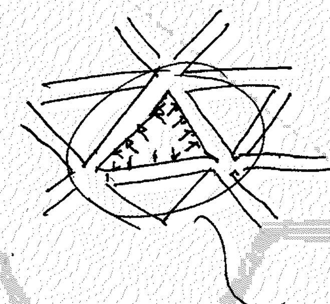
Basic Issues - Heat Sinks

Pressure drop and cell burst overpressure (McDowell, 1999)



$$\frac{P_i}{\sigma_{ys}} = \begin{cases} \frac{16}{9}\left(\frac{\rho}{\rho_s}\right)^2 & \text{for triangular cells} \\ \left(\frac{\rho}{\rho_s}\right)^2 & \text{for square cells} \end{cases}$$

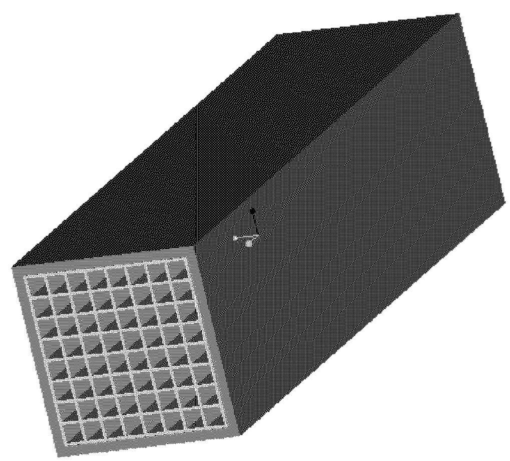


Slightly lower due to shift of neutral axis due to cell wall extension

For a relative density of 10%, P_i is approx. 1% of the plastic flow stress, limited by S_u , i.e.

Al alloys $\longrightarrow$ 300-500 psi
Ni alloys $\longrightarrow$ 1000-2000 psi
Cu alloys $\longrightarrow$ 200-400 psi

LCMs as Structural Materials



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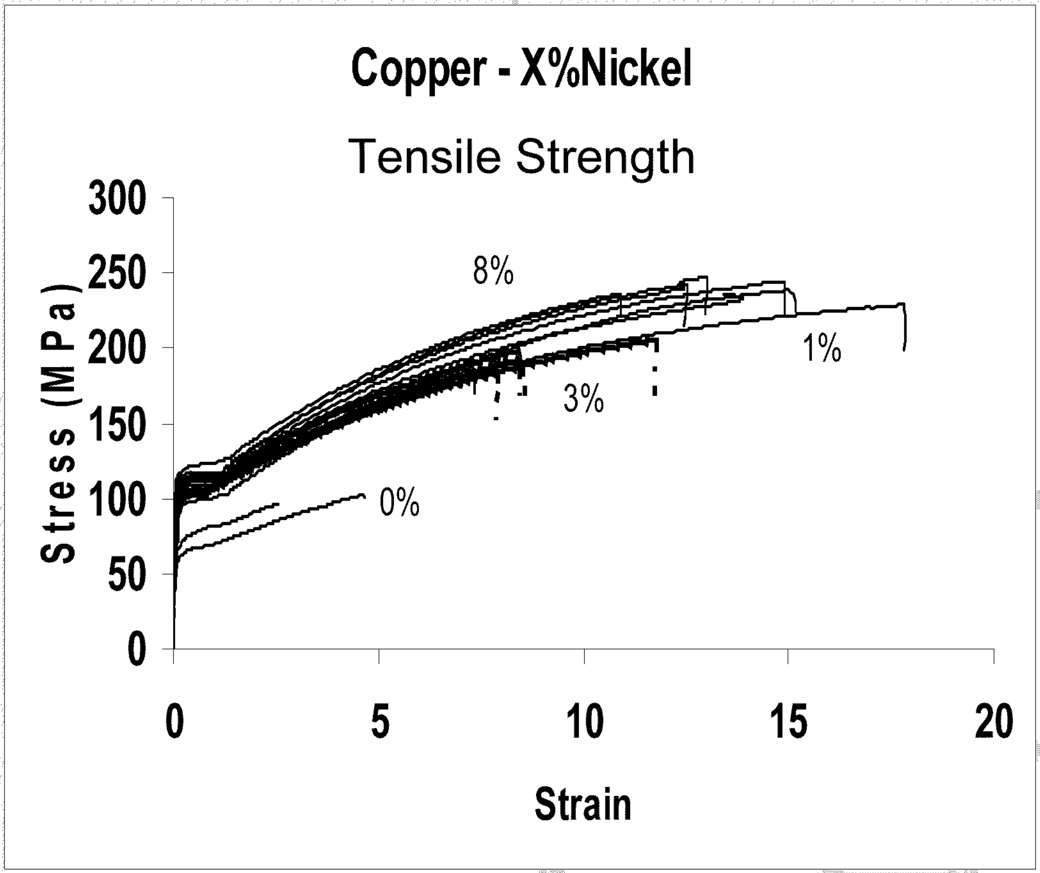
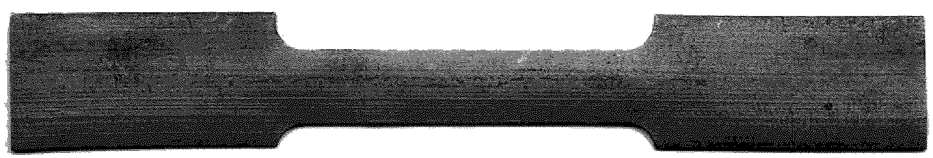
Metallurgical Properties

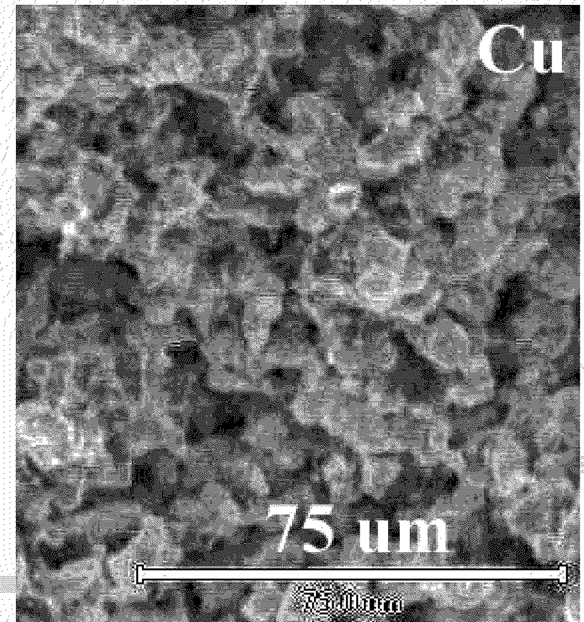
Copper Alloys

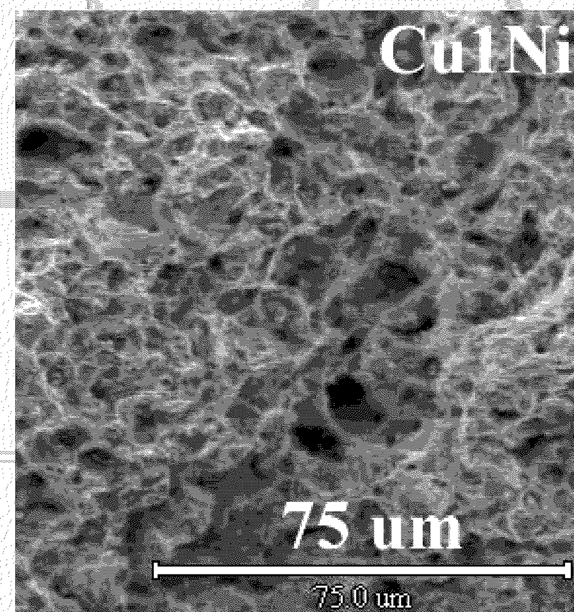




Thickness = 0.56 mm Width = 5.72 mm

Fracture Surface





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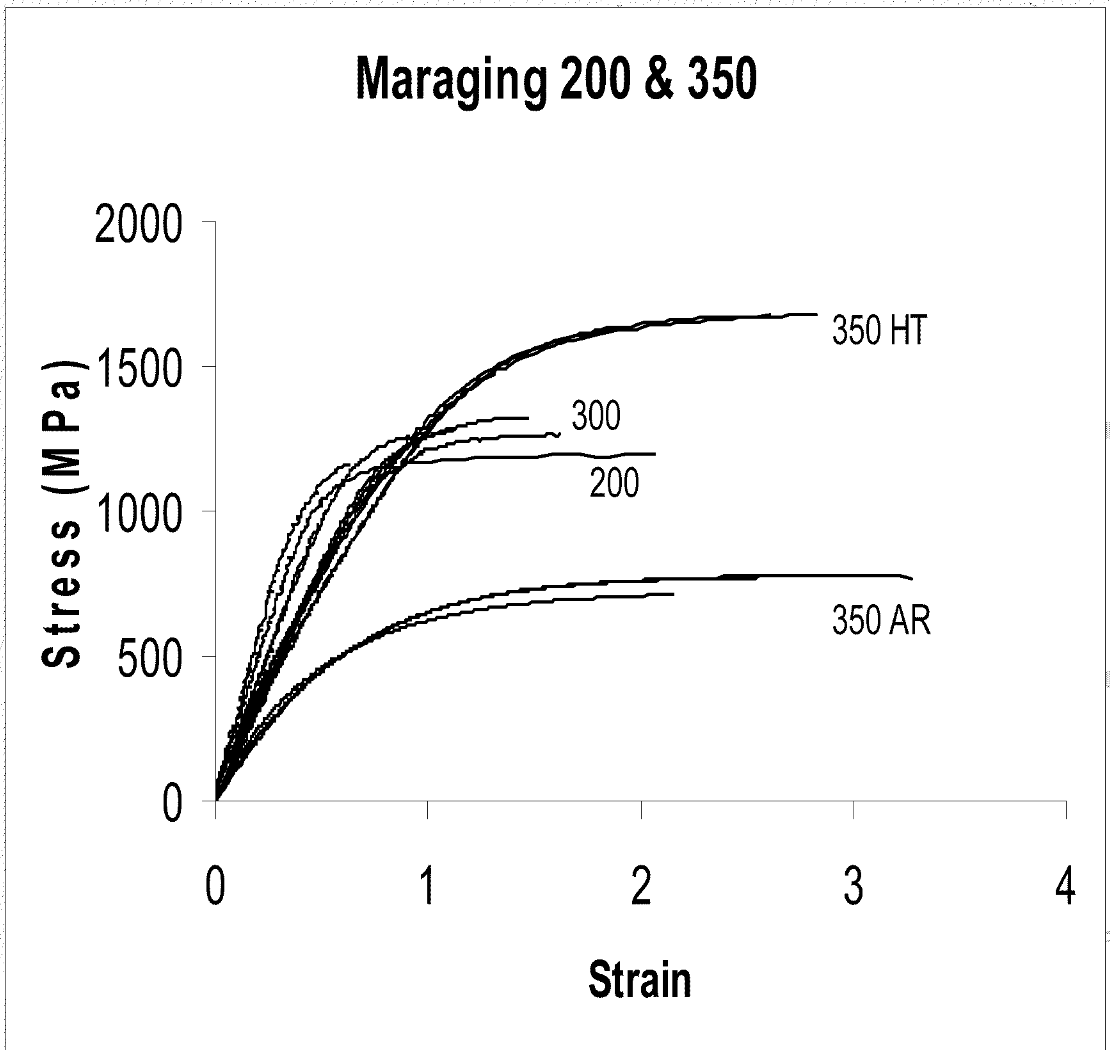
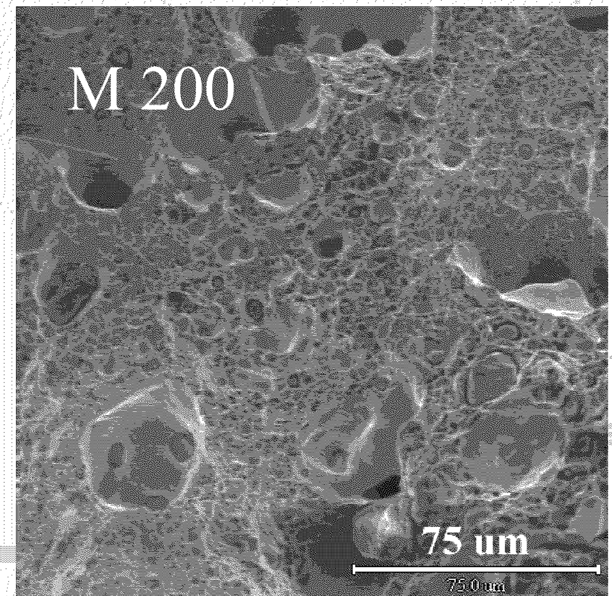
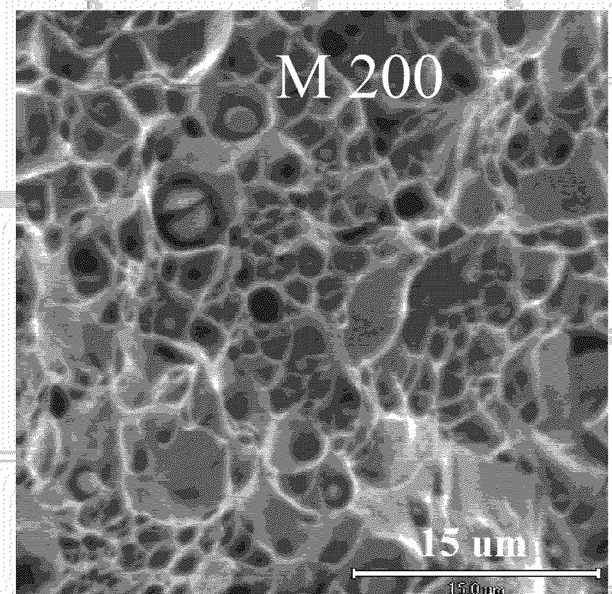
Metallurgical Properties

Maraging Steel

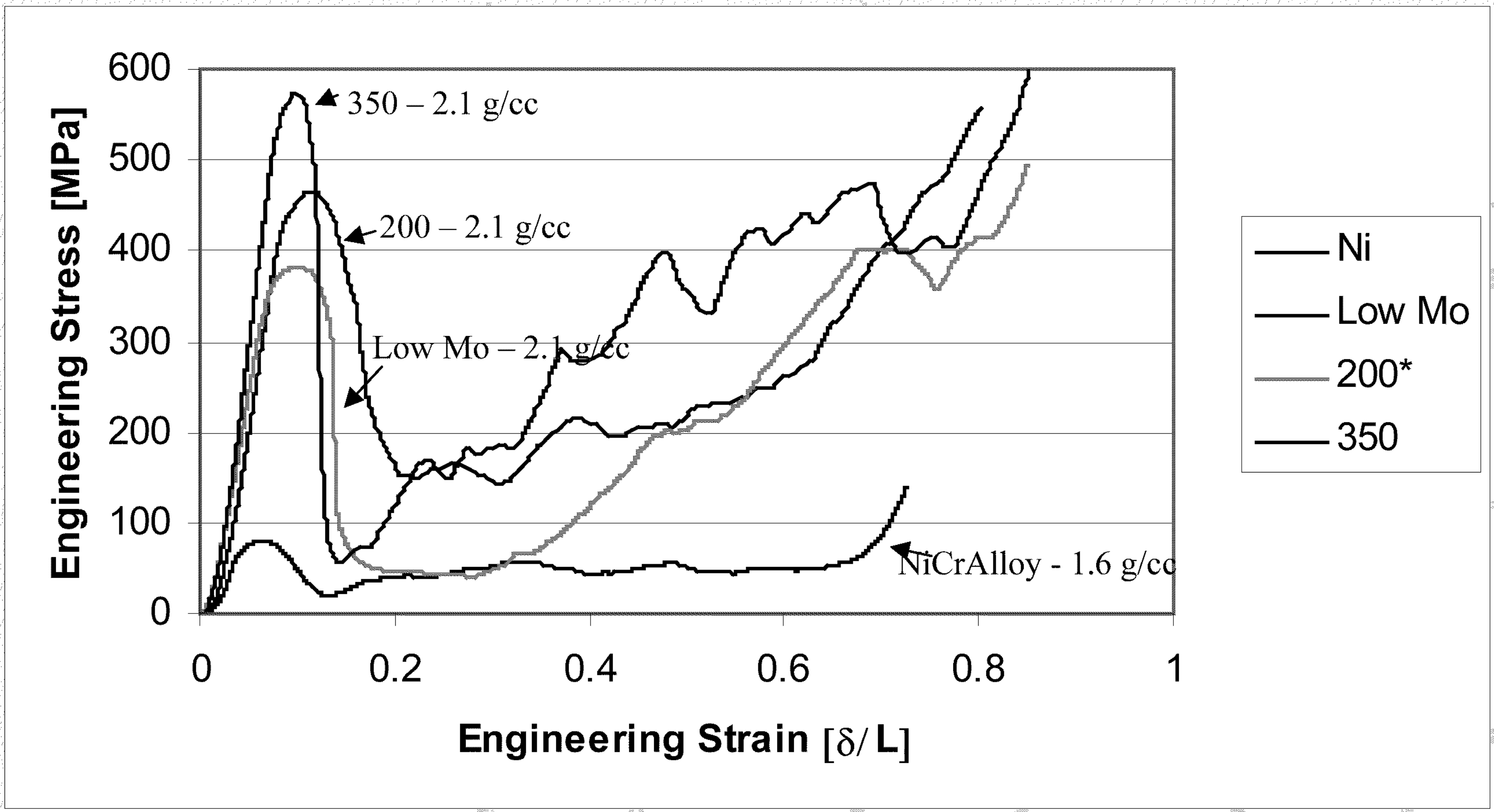
Tensile Strength/ Fracture Surface







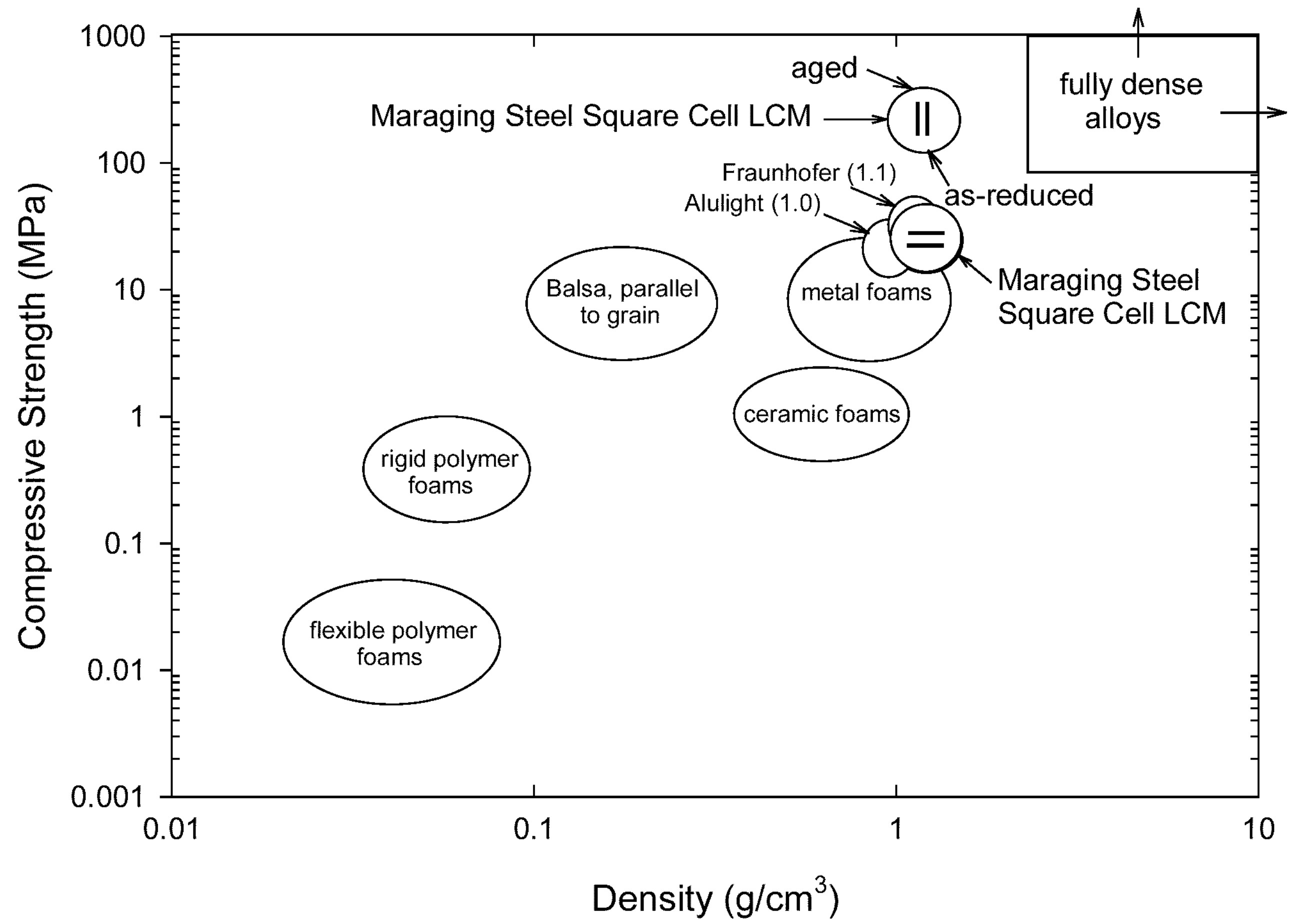
Strength of Square Cell Maraging Steel LCM Loaded Parallel to Axis



* = Larger Cell Array (8x8)

Low Mo w/ HT2

Compressive Strength Comparison: LCMs



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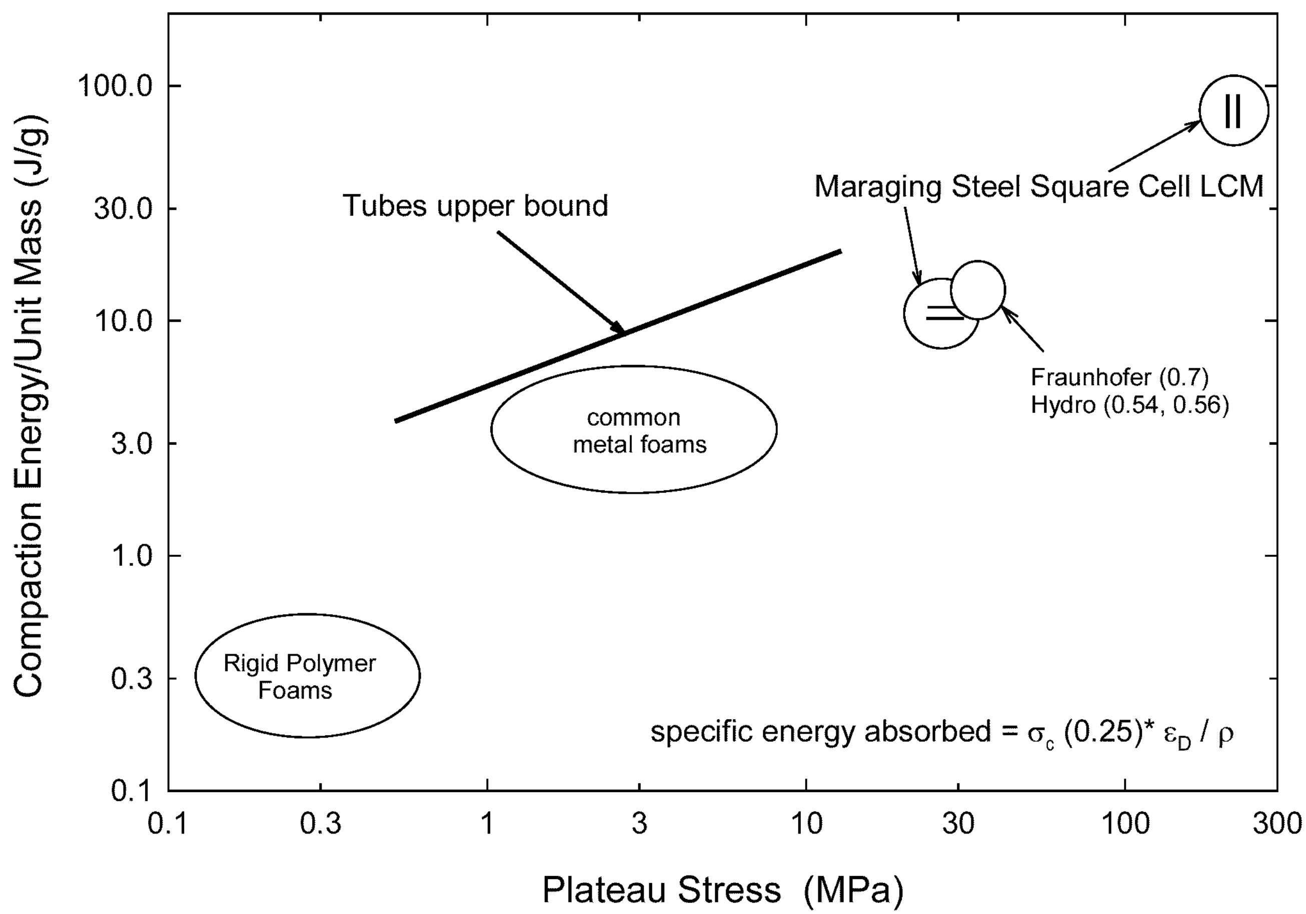
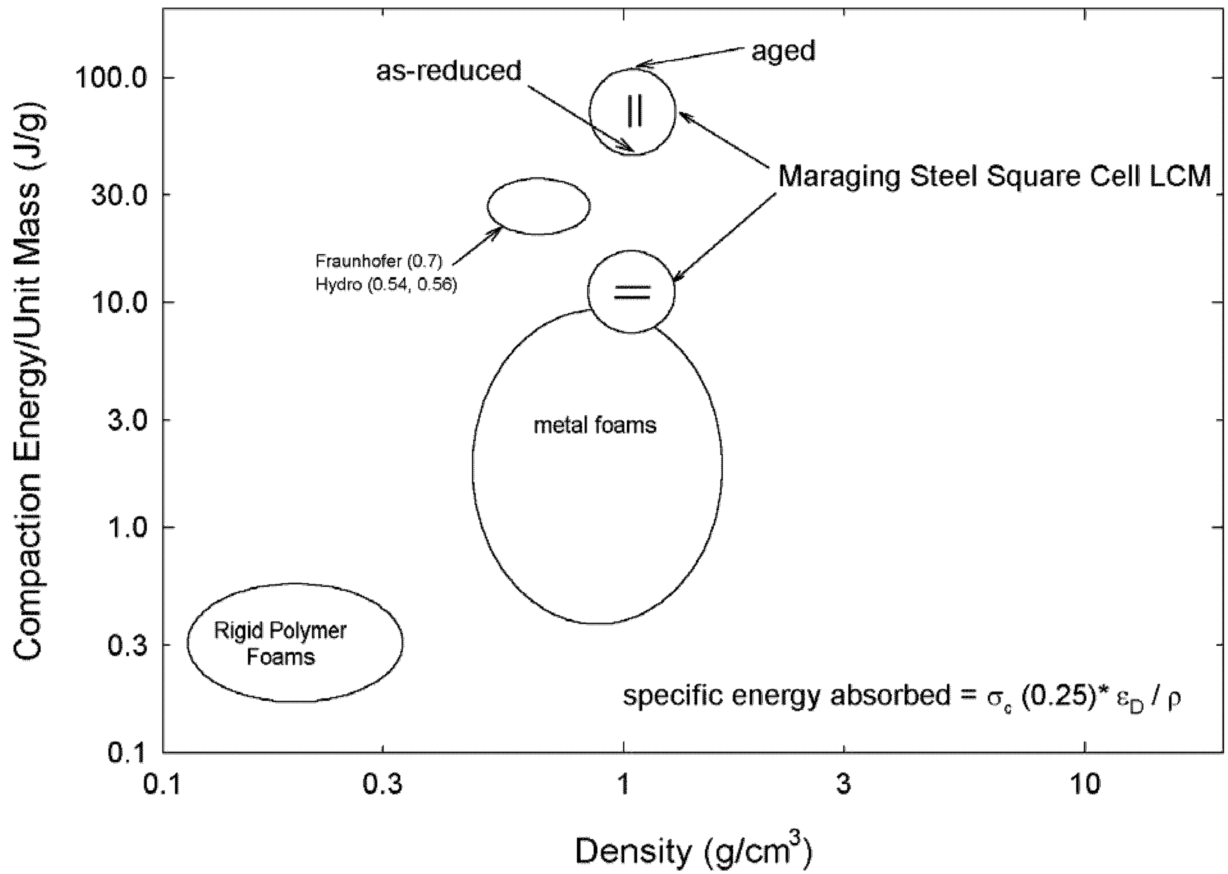
Energy Absorption per Unit Mass



Specific Energy Absorption Comparison: LCMs



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LinCelloy

CONCLUSIONS

Processing of High Conductivity Microchannel Linear Cellular Materials

! Models for paste properties and LCS die designs are nearing completion.

! Quality of honeycomb extrusion has improved dramatically and defects have been minimized.

! Metallurgical properties of alloys from direct oxide reduction can approach those of conventionally processed alloys.

! Due to low pressure drops and thin walls, high efficiency heat exchangers appear feasible for LCAs in a variety of applications.

! High energy adsorption for LCM in high strength alloys has been demonstrated.